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Sum et al.

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(54) **DISTRIBUTED SMART GRID PROCESSING**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 48 days.

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(51) **Int. Cl.**
G06F 15/173 (2006.01)
G01R 25/00 (2006.01)
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(52) **U.S. Cl.**
CPC ***G01R 25/00*** (2013.01); ***G01R 21/00*** (2013.01); ***H02J 3/00*** (2013.01); ***H02J 3/24*** (2013.01);
(Continued)

(58) **Field of Classification Search**
USPC 709/224
See application file for complete search history.

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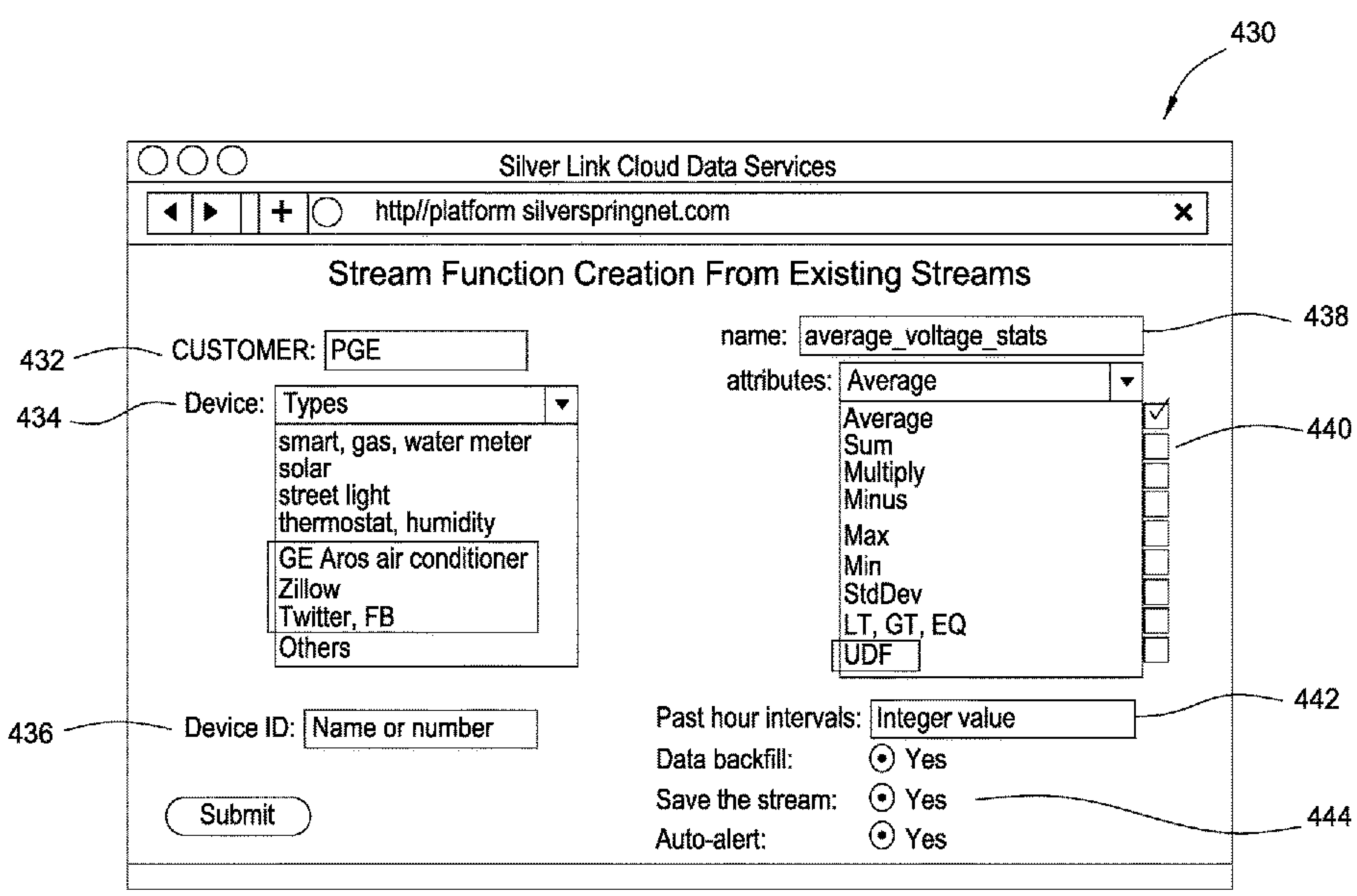
(57) **ABSTRACT**

Nodes within a wireless mesh network are configured to monitor time series data associated with a utility network, including voltage fluctuations, current levels, temperature data, humidity measurements, and other observable physical quantities. The nodes execute stream functions to process the recorded time series data and generate data streams. The node is configured to transmit generated data streams to neighboring nodes. A neighboring node may execute other stream functions to process the received data stream(s), thereby generating additional data streams. A server coupled to the wireless mesh network collects and processes the data streams to identify events occurring within the network.

26 Claims, 12 Drawing Sheets



Related U.S. Application Data

filed on Sep. 3, 2014, provisional application No. 62/094,907, filed on Dec. 19, 2014.

(51) **Int. Cl.**

H02J 3/00 (2006.01)
G01R 21/00 (2006.01)
H04L 29/08 (2006.01)
H04L 29/06 (2006.01)
H04L 12/24 (2006.01)
H02J 13/00 (2006.01)
H02J 3/24 (2006.01)
H04L 12/26 (2006.01)
H02J 3/06 (2006.01)

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CPC ***H02J 13/00022*** (2020.01); ***H02J 13/0075*** (2013.01); ***H04L 41/0803*** (2013.01); ***H04L 41/0896*** (2013.01); ***H04L 41/12*** (2013.01); ***H04L 43/0876*** (2013.01); ***H04L 43/0888*** (2013.01); ***H04L 67/125*** (2013.01); ***H04L 67/16*** (2013.01); ***H04L 69/28*** (2013.01); *H02J 3/007* (2020.01); *H02J 3/06* (2013.01); *H02J 2203/20* (2020.01); *H04L 43/04* (2013.01); *Y02E 60/00* (2013.01); *Y04S 40/00* (2013.01); *Y04S 40/126* (2013.01); *Y04S 40/18* (2018.05); *Y04S 40/20* (2013.01)

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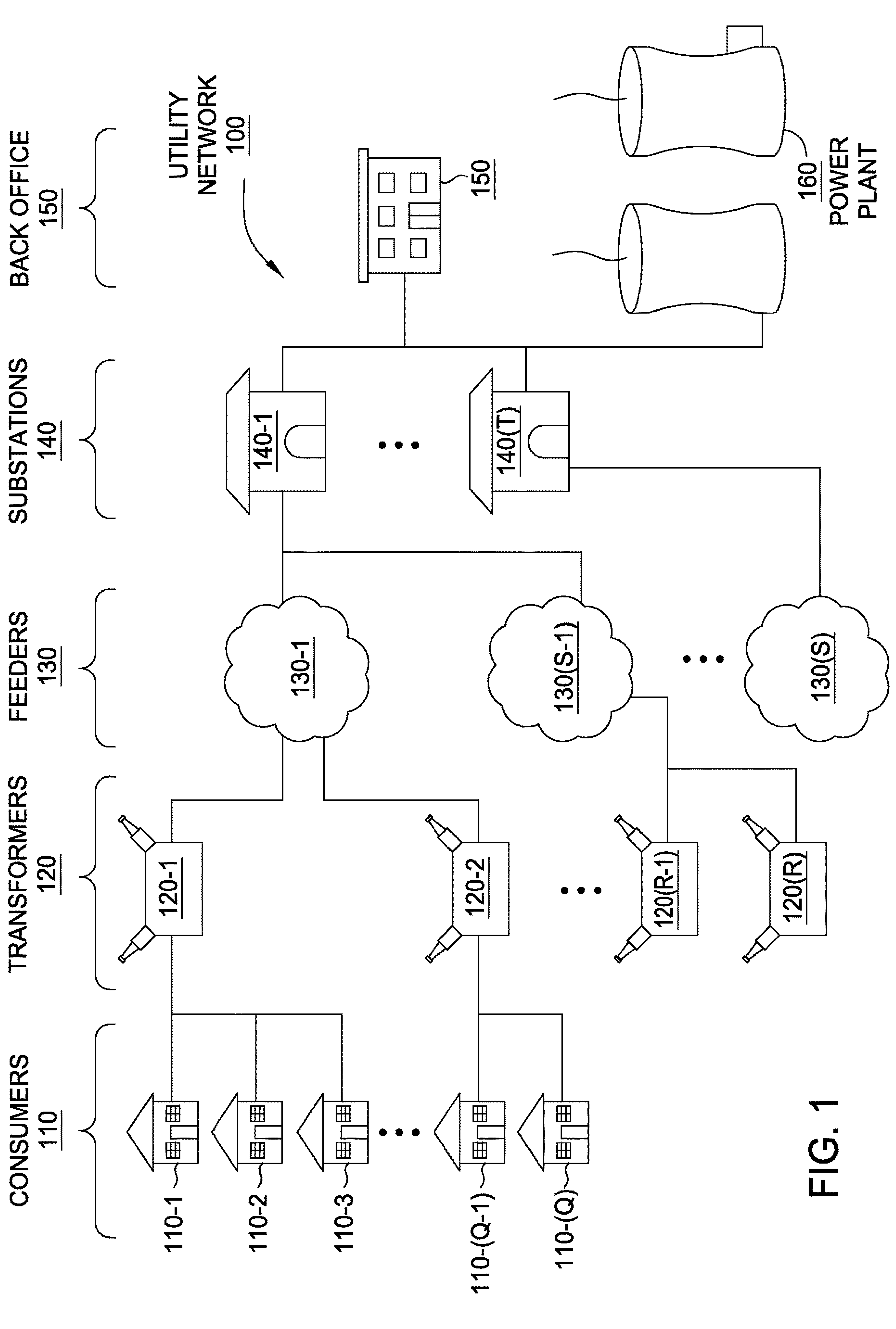
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SUBSTATIONS 140
FEEDERS 130
TRANSFORMERS 120
CONSUMERS 110
UTILITY NETWORK 100
150
160 POWER PLANT
140-1
140(T)
130-1
130(S-1)
130(S)
120-1
120-2
120(R-1)
120(R)
110-1
110-2
110-3
110-(Q-1)
110-(Q)

FIG. 1

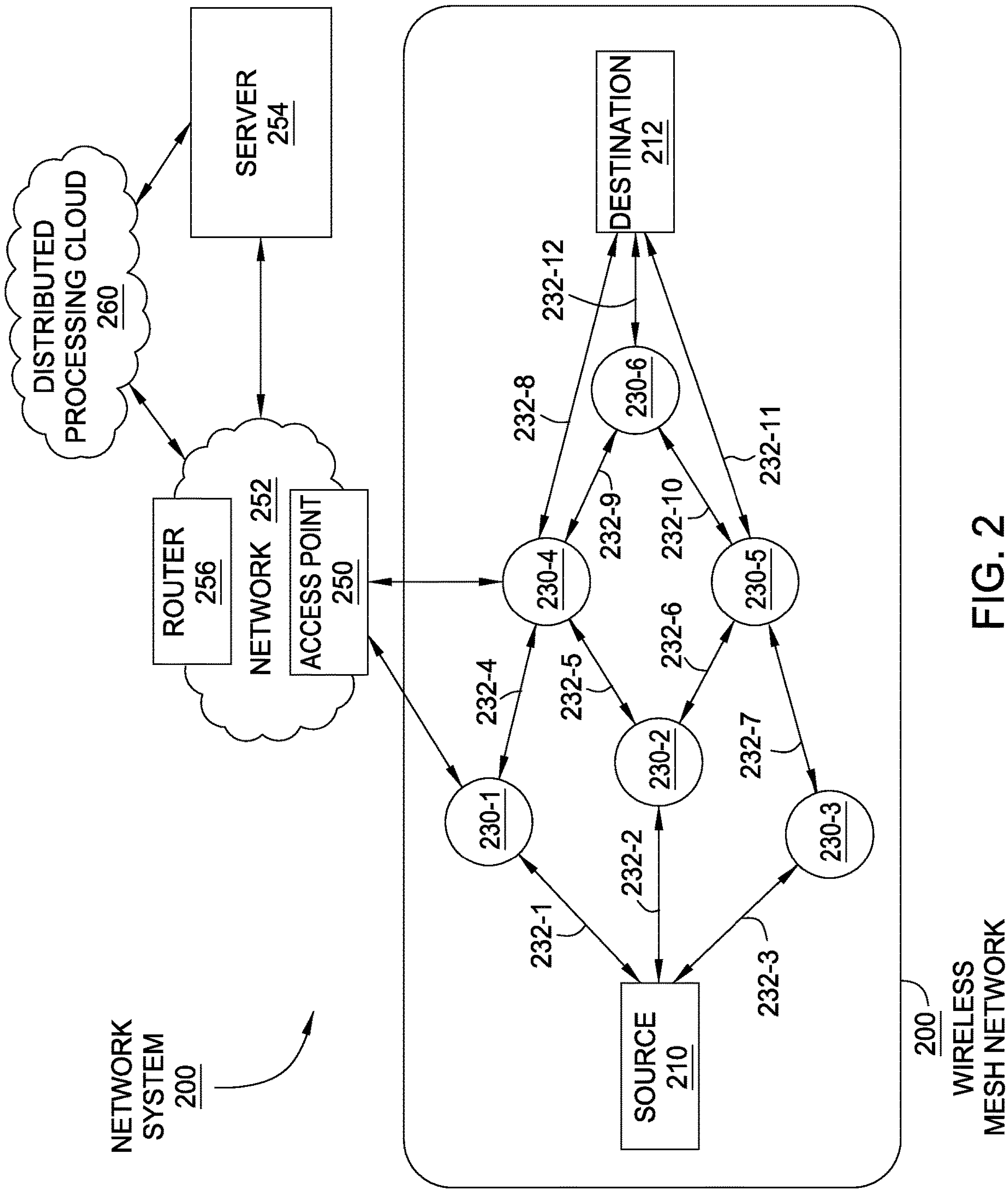
NETWORK SYSTEM 200
DISTRIBUTED PROCESSING CLOUD 260
SERVER 254
ROUTER 256
NETWORK 252
ACCESS POINT 250
DESTINATION 212
SOURCE 210
230-1
230-2
230-3
230-4
230-5
230-6
232-1
232-2
232-3
232-4
232-5
232-6
232-7
232-8
232-9
232-10
232-11
232-12
200 WIRELESS MESH NETWORK

FIG. 2

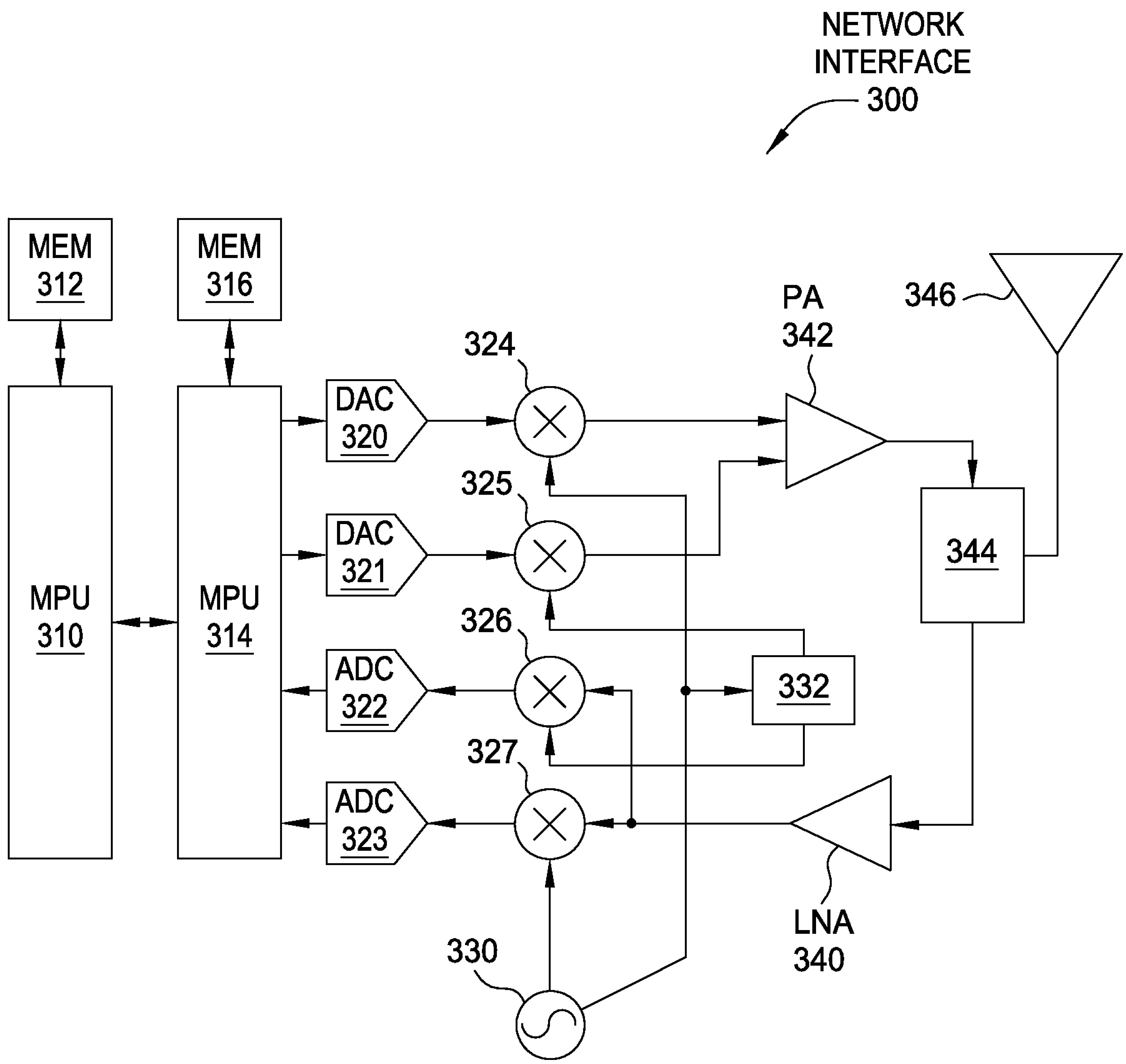
NETWORK
INTERFACE
300
MEM
312
MEM
316
MPU
310
MPU
314
DAC
320
DAC
321
ADC
322
ADC
323
324
325
326
327
330
332
PA
342
344
346
LNA
340

FIG. 3

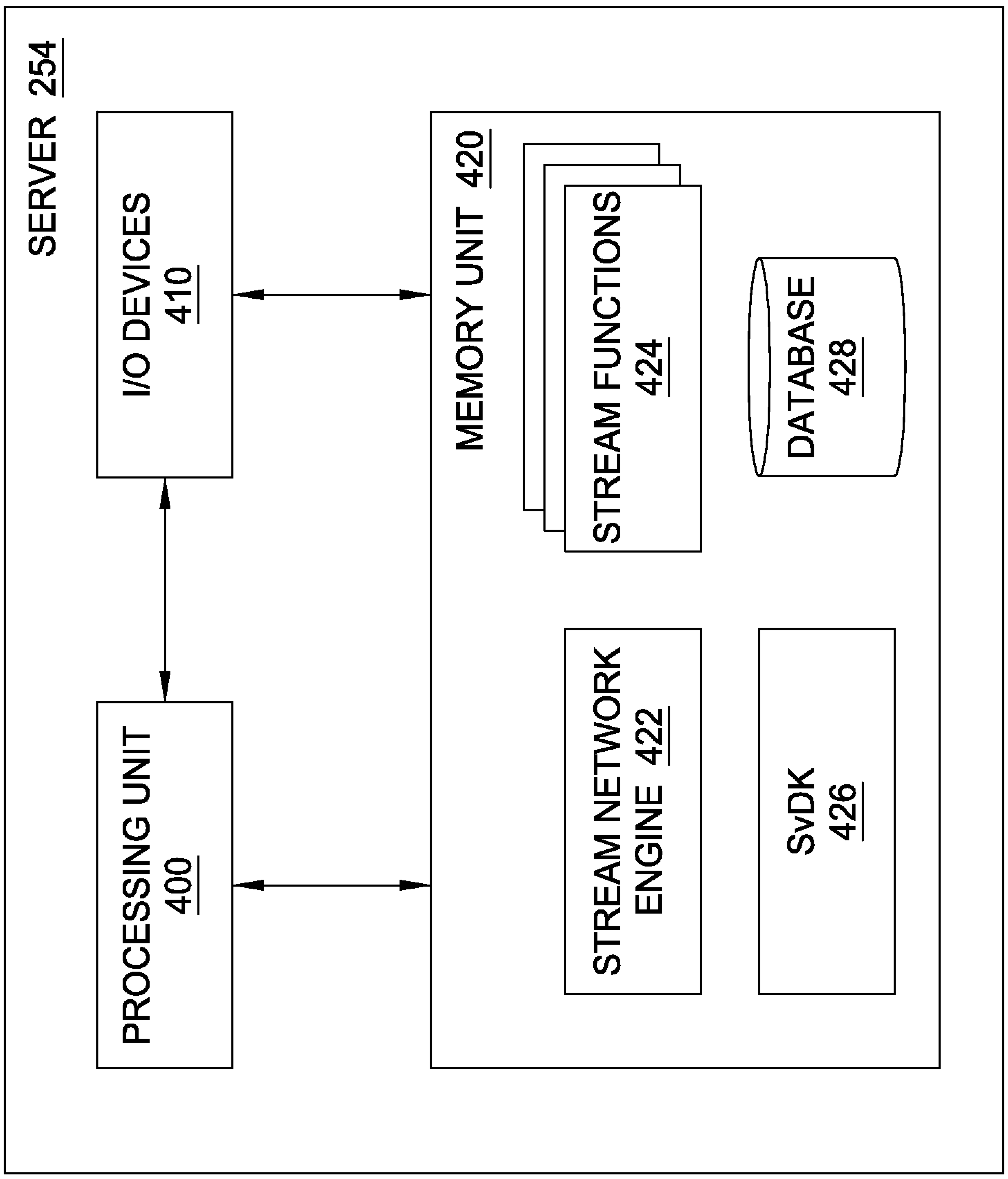
SERVER 254
I/O DEVICES 410
PROCESSING UNIT 400
MEMORY UNIT 420
STREAM FUNCTIONS 424
DATABASE 428
STREAM NETWORK ENGINE 422
SvDK 426

FIG. 4A

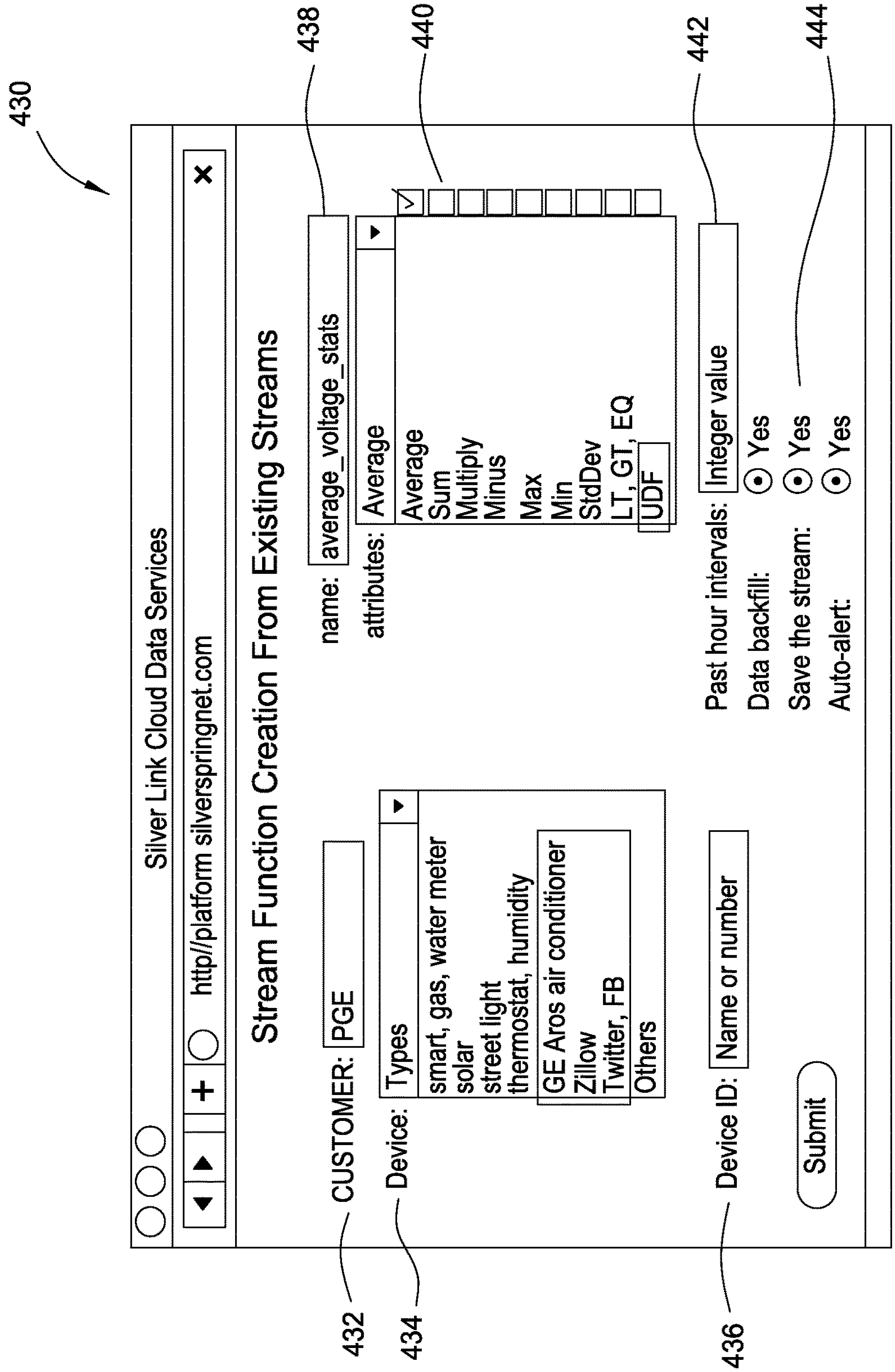
430
Silver Link Cloud Data Services
http//platform silverspringnet.com
Stream Function Creation From Existing Streams
CUSTOMER: PGE
Device: Types
smart, gas, water meter
solar
street light
thermostat, humidity
GE Aros air conditioner
Zillow
Twitter, FB
Others
Device ID: Name or number
Submit
name: average_voltage_stats
attributes: Average
Average
Sum
Multiply
Minus
Max
Min
StdDev
LT, GT, EQ
UDF
Past hour intervals: Integer value
Data backfill: Yes
Save the stream: Yes
Auto-alert: Yes
432
434
436
438
440
442
444

FIG. 4B

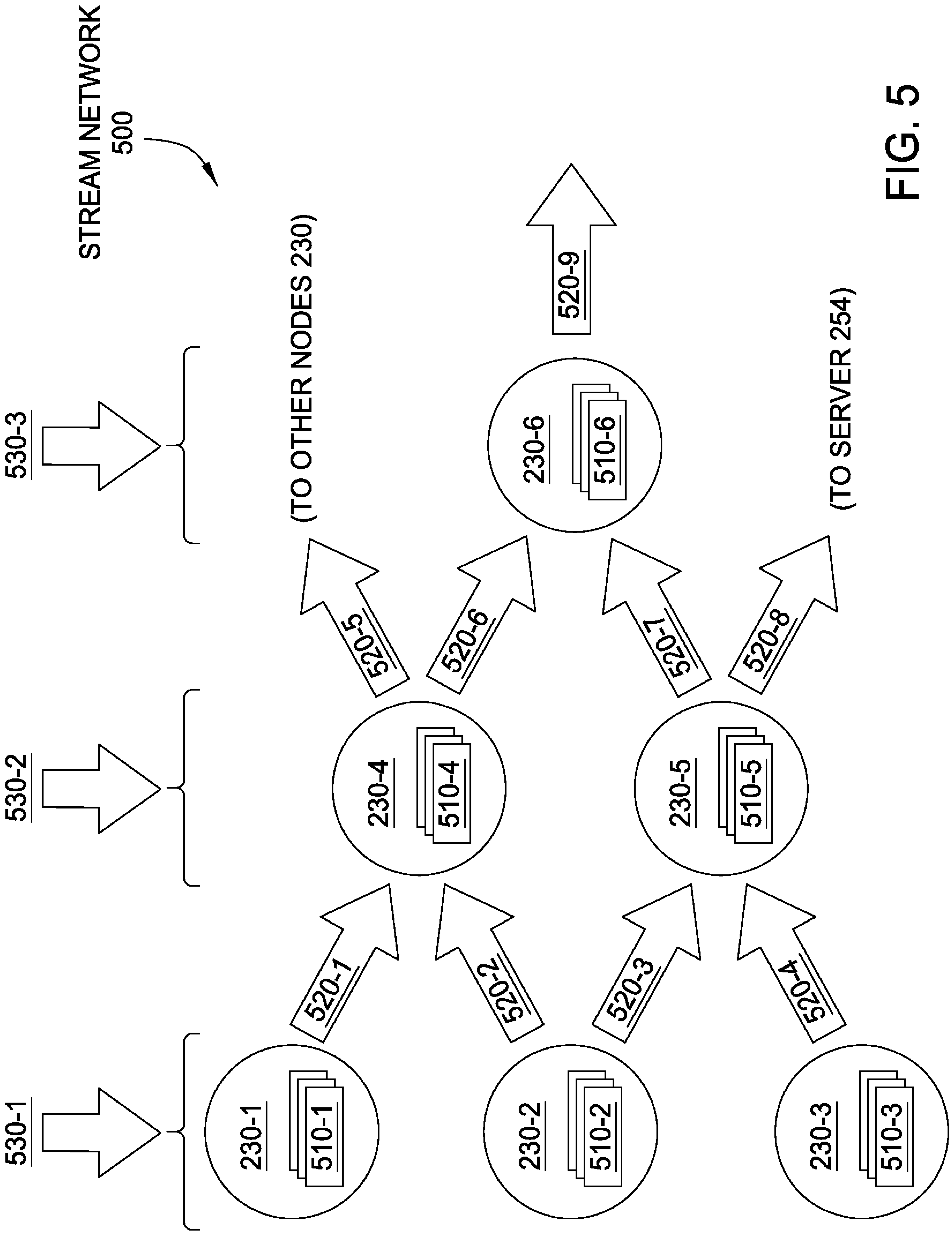
STREAM NETWORK
500
530-1
530-2
530-3
230-1
510-1
230-2
510-2
230-3
510-3
230-4
510-4
230-5
510-5
230-6
510-6
520-1
520-2
520-3
520-4
520-5
520-6
520-7
520-8
520-9
(TO OTHER NODES 230)
(TO SERVER 254)

FIG. 5

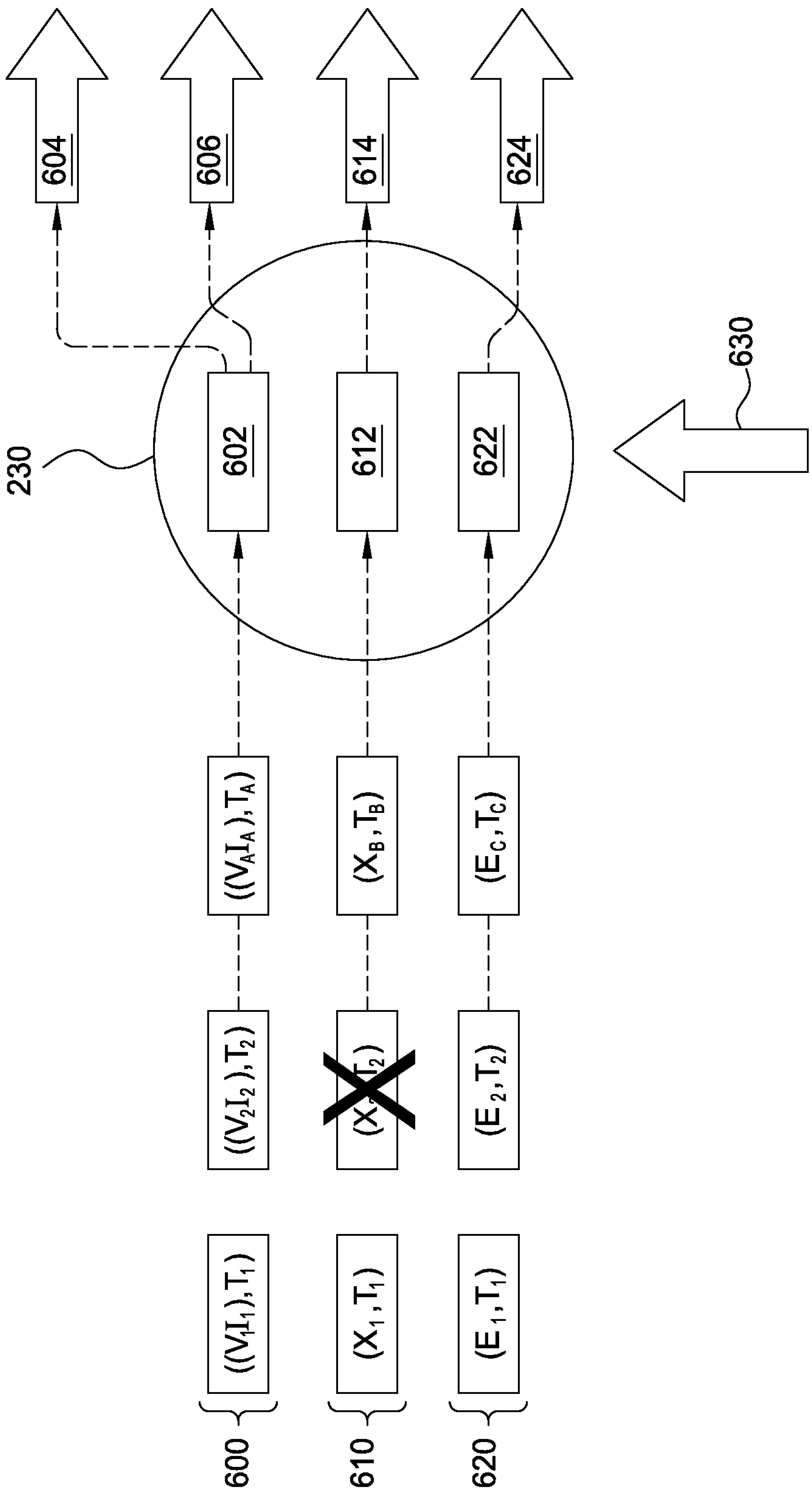
604
606
614
624
230
602
612
622
630
$((V_A I_A),T_A)$
(X_B,T_B)
(E_C,T_C)
$((V_2 I_2),T_2)$
(E_2,T_2)
$((V_1 I_1),T_1)$
(X_1,T_1)
(E_1,T_1)
600
610
620

FIG. 6

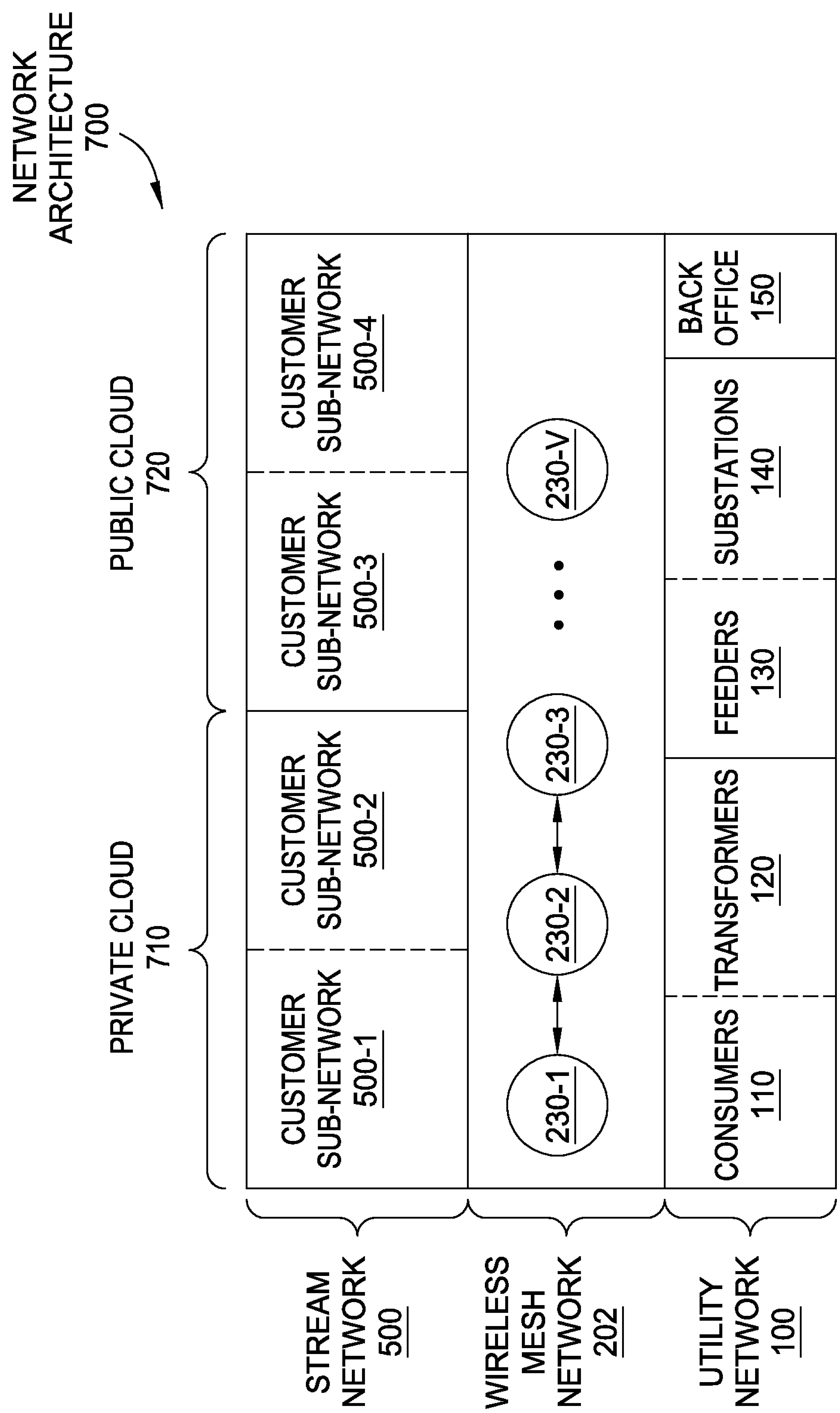
NETWORK ARCHITECTURE 700
PRIVATE CLOUD 710
PUBLIC CLOUD 720
CUSTOMER SUB-NETWORK 500-1
CUSTOMER SUB-NETWORK 500-2
CUSTOMER SUB-NETWORK 500-3
CUSTOMER SUB-NETWORK 500-4
230-1
230-2
230-3
230-V
CONSUMERS 110
TRANSFORMERS 120
FEEDERS 130
SUBSTATIONS 140
BACK OFFICE 150
STREAM NETWORK 500
WIRELESS MESH NETWORK 202
UTILITY NETWORK 100

FIG. 7

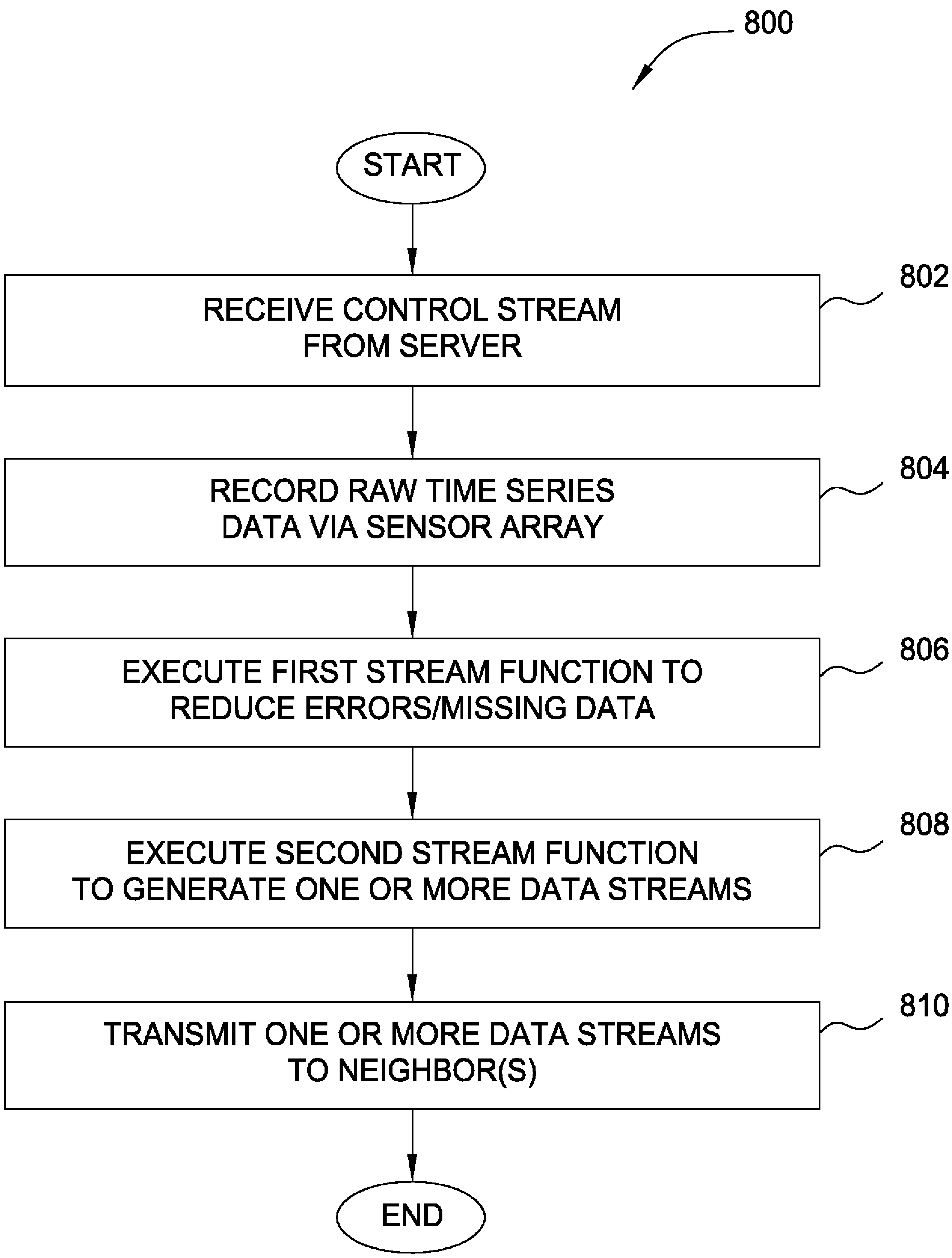
800
START
RECEIVE CONTROL STREAM FROM SERVER
802
RECORD RAW TIME SERIES DATA VIA SENSOR ARRAY
804
EXECUTE FIRST STREAM FUNCTION TO REDUCE ERRORS/MISSING DATA
806
EXECUTE SECOND STREAM FUNCTION TO GENERATE ONE OR MORE DATA STREAMS
808
TRANSMIT ONE OR MORE DATA STREAMS TO NEIGHBOR(S)
810
END

FIG. 8

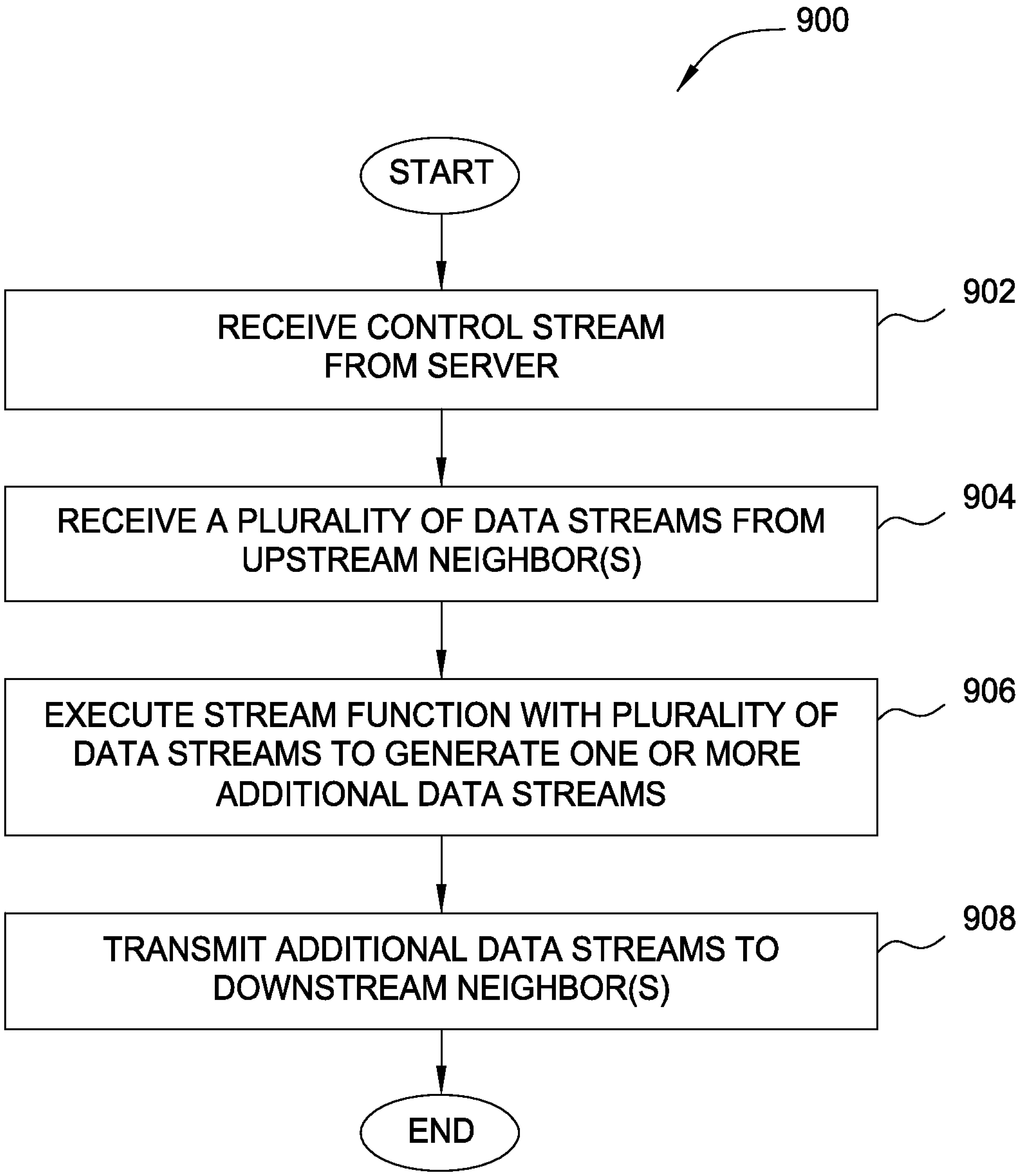
900
START
RECEIVE CONTROL STREAM FROM SERVER
902
RECEIVE A PLURALITY OF DATA STREAMS FROM UPSTREAM NEIGHBOR(S)
904
EXECUTE STREAM FUNCTION WITH PLURALITY OF DATA STREAMS TO GENERATE ONE OR MORE ADDITIONAL DATA STREAMS
906
TRANSMIT ADDITIONAL DATA STREAMS TO DOWNSTREAM NEIGHBOR(S)
908
END

FIG. 9

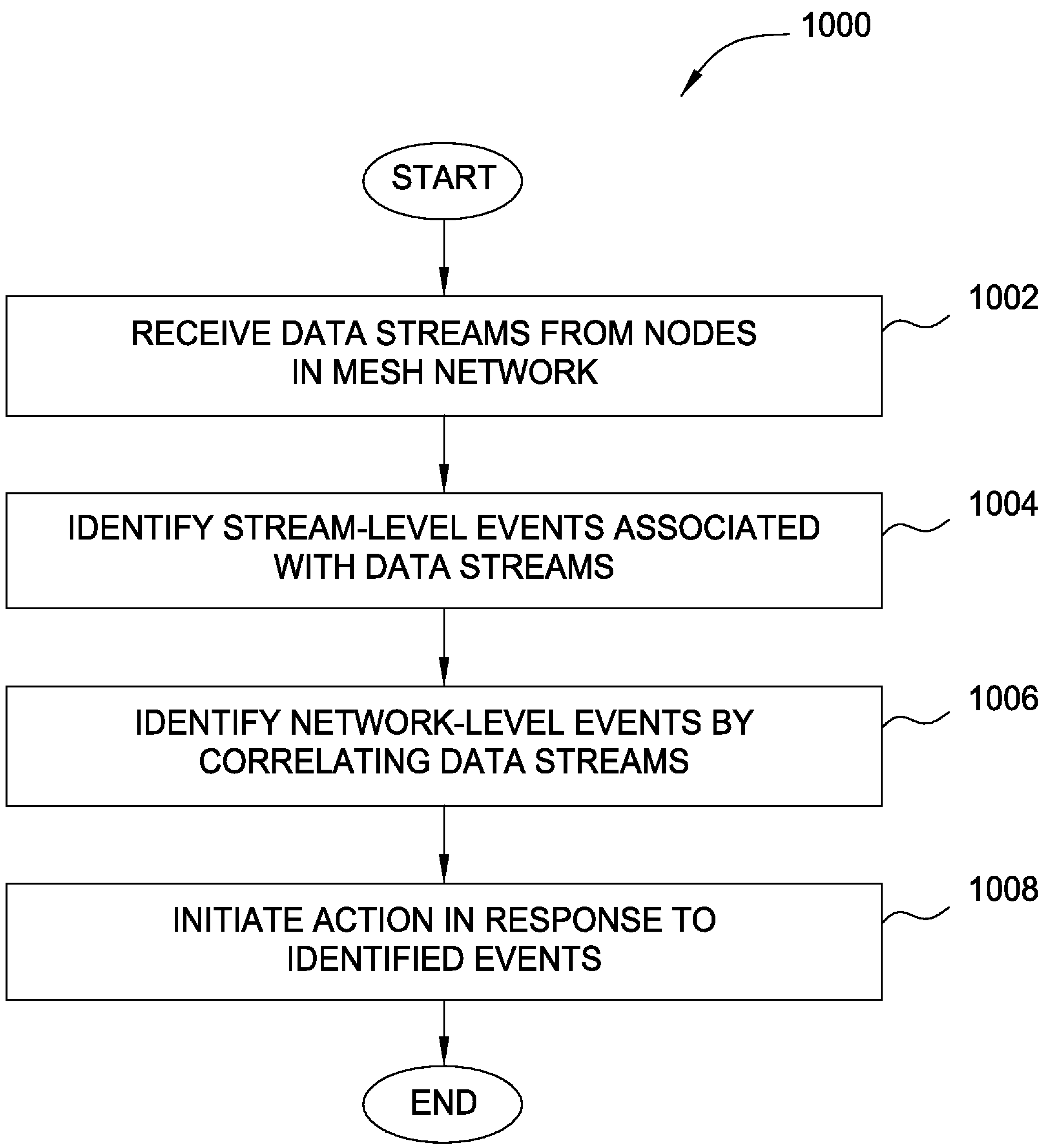
1000
START
RECEIVE DATA STREAMS FROM NODES IN MESH NETWORK
1002
IDENTIFY STREAM-LEVEL EVENTS ASSOCIATED WITH DATA STREAMS
1004
IDENTIFY NETWORK-LEVEL EVENTS BY CORRELATING DATA STREAMS
1006
INITIATE ACTION IN RESPONSE TO IDENTIFIED EVENTS
1008
END

FIG. 10

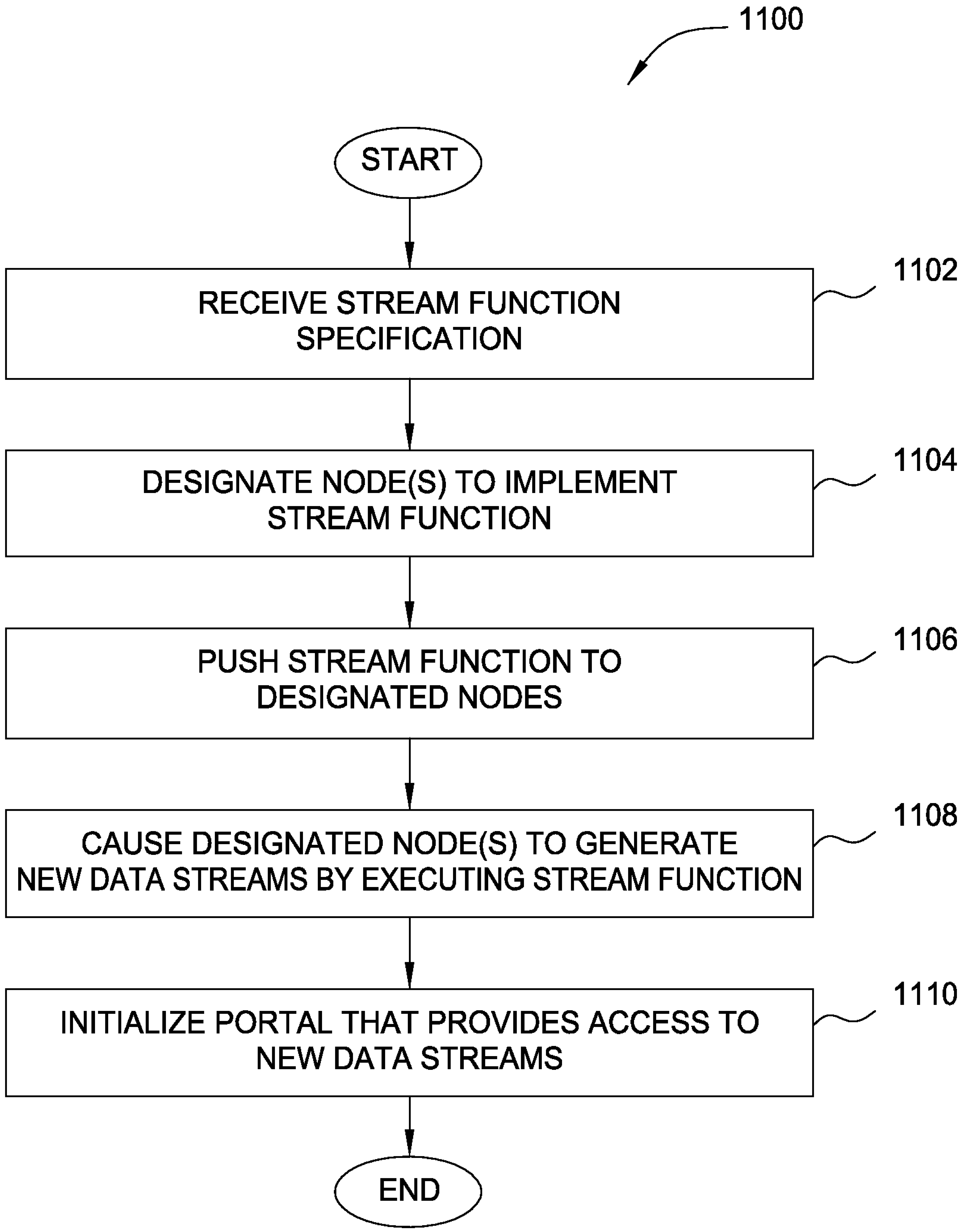
1100
START
RECEIVE STREAM FUNCTION SPECIFICATION
1102
DESIGNATE NODE(S) TO IMPLEMENT STREAM FUNCTION
1104
PUSH STREAM FUNCTION TO DESIGNATED NODES
1106
CAUSE DESIGNATED NODE(S) TO GENERATE NEW DATA STREAMS BY EXECUTING STREAM FUNCTION
1108
INITIALIZE PORTAL THAT PROVIDES ACCESS TO NEW DATA STREAMS
1110
END

FIG. 11

DISTRIBUTED SMART GRID PROCESSING

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. provisional patent application titled "Smart Grid Processing to Evaluate Grid Conditions," filed on Mar. 10, 2014, and having Ser. No. 61/950,425, U.S. provisional patent application titled "Distributed Smart Grid Processing," filed on Sep. 3, 2014 and having Ser. No. 62/045,423, and United States provisional patent application titled "Distributed Smart Grid Processing," filed on Dec. 19, 2014 and having Ser. No. 62/094,907. The subject matter of each of these related applications is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

Embodiments of the present invention relate generally to network architecture and semantics for distributed processing on a data pipeline, and, more specifically, to distributed smart grid processing.

Description of the Related Art

A conventional electricity distribution infrastructure typically includes a plurality of energy consumers, such as houses, business, and so forth, coupled to a grid of intermediate distribution entities, such as transformers, feeders, substations, etc. The grid of distribution entities draws power from upstream power plants and distributes that power to the downstream consumers. In a modern electricity distribution infrastructure, the consumers, as well as the intermediate distribution entities, may include smart meters and other monitoring hardware coupled together to form a mesh network. The smart meters and other measurement and control devices collect data that reflects the operating state of the grid, as well as consumption and utilization of the grid, and then report the collected data, via the mesh network, to a centralized grid management facility, often referred to as the "back office." Such a configuration is commonly known as a "smart grid."

In a conventional smart grid, the back office receives a multitude of real-time data from the various smart meters, stores that data in a database as historical data, and then performs different computations with the historical data to identify specific operating conditions associated with the grid. Those conditions may include electrical events, such as sags or swells, as well as physical events, such as downed power lines or overloaded transformers, among other possibilities. The back office usually includes centralized processing hardware, such as a server room or datacenter, configured to execute "big data" processing across the smart meter data stored in the database. Such big data processing may include warehouse processing techniques or batch processing, among other techniques.

One problem with approach described above is that, with the expansion of smart grid infrastructure, the amount of data that must be transmitted to the back office, stored in the database, and then processed, is growing quickly. Consequently, the mesh network across which the smart meters transmit data may become over-burdened with traffic and, therefore, suffer from throughput issues. In addition, the processing hardware implemented by the back office may quickly become obsolete as the amount of data that must be processed grows. As a general matter, the infrastructure required to transport and process data generated by a smart grid cannot scale as quickly as the amount of data that is generated.

As the foregoing illustrates, what is needed in the art is a more effective approach for evaluating real-time and historical conditions that arise within a smart grid architecture.

SUMMARY OF THE INVENTION

One embodiment of the present invention sets forth a computer-implemented method for generating a time series of data values, including obtaining a first time series of data values having a first type, obtaining a second time series of data values having a second type, executing a first stream function on at least a portion of the first time series and at least a portion of the second time series to generate a third time series of data values having a third type, and transmitting the third time series to at least one network management entity configured to manage at least a portion of a network.

At least one advantage of the techniques set forth herein is that data processing occurs at edges of the network, i.e., locations where the data is actually collected. Thus, complex processing involving the network as a whole can be broken down into granular, atomic processing steps that are performed, in a distributed and real-time fashion, across the network.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIG. **1** illustrates a utility network configured to implement an electricity distribution infrastructure, according to one embodiment of the present invention;

FIG. **2** illustrates a mesh network that operates in conjunction with the utility network of FIG. **1**, according to one embodiment of the present invention;

FIG. **3** illustrates a network interface configured to implement multi-channel operation, according to one embodiment of the present invention;

FIG. **4**A illustrates a server coupled to the mesh network of FIG. **2**, according to one embodiment of the present invention;

FIG. **4**B illustrates a graphical user interface that may be used to generate a stream function, according to one embodiment of the present invention;

FIG. **5** illustrates a stream network configured to operate in conjunction with the mesh network of FIG. **2**, according to one embodiment of the present invention;

FIG. **6** illustrates an exemplary scenario where a node of FIG. **5** generates a set of data streams based on recorded time series data, according to one embodiment of the present invention;

FIG. **7** illustrates an network architecture that includes the utility network of FIG. **1**, the mesh network of FIG. **2**, and the stream network of FIG. **5**, according to one embodiment of the present invention;

FIG. **8** is a flow diagram of method steps for generating a data stream based on recorded time series data, according to one embodiment of the present invention;

FIG. **9** is a flow diagram of method steps for generating one or more data streams based on one or more received data streams, according to one embodiment of the present invention;

FIG. **10** is a flow diagram of method steps for evaluating conditions associated with the network architecture of FIG. **7**, according to one embodiment of the present invention; and

FIG. **11** is a flow diagram of method steps for configuring a node within the stream network of FIG. **5** to generate a data stream, according to one embodiment of the present invention.

DETAILED DESCRIPTION

In the following description, numerous specific details are set forth to provide a more thorough understanding of the present invention. However, it will be apparent to one of skill in the art that the present invention may be practiced without one or more of these specific details. In other instances, well-known features have not been described in order to avoid obscuring the present invention.

System Overview

In the following disclosure, a multi-layered network architecture is described that includes a utility network, illustrated in FIG. **1**, a wireless mesh network, illustrated in FIG. **2**, and a stream network, illustrated in FIG. **5**. The utility network includes hardware configured to transport and distribute electricity. The wireless mesh network includes hardware nodes residing within elements of that utility network, where those nodes are configured to execute firmware and/or software to (i) monitor the utility network and (ii) establish and maintain the wireless mesh network. In addition, the nodes are also configured to execute firmware and/or software to generate the stream network. The stream network includes time series data that is generated and processed by the nodes, and shared between nodes via the wireless mesh network. The stream network operates above the wireless mesh network, which, in turn, operates above the electricity distribution layer.

FIG. **1** illustrates a utility network **100** configured to implement an electricity distribution infrastructure, according to one embodiment of the present invention. As shown, utility network **100** includes consumer **110**, transformers **120**, feeders **130**, substations **140**, and a back office **150**, coupled together in a sequence. Substations **140(1)** through **140**(T) are configured to draw power from one or more power plants **160** and to distribute that power to feeders **130(1)** through **130**(S). Feeders **130**, in turn, distribute that power to transformers **120(1)** through **120**(R). Transformers **120** step down high-voltage power transported by feeders **130** to a low-voltage power, and then transmit the low-voltage power to consumers **110(1)** through **110**(Q). Consumers **110** include houses, business, and other consumers of power.

Each of consumers **110**, transformers **120**, feeders **130**, and substations **140** may include one or more instances of a node. In the context of this disclosure, a "node" refers to a computing device that is coupled to an element of utility network **100** and includes a sensor array and a wireless transceiver. An exemplary node is described below in conjunction with FIG. **3**. Each such node is configured to monitor operating conditions associated with a specific portion of the utility network **100**. For example, consumer **110(1)** could include a node configured to monitor a number of kilowatt-hours consumed by consumer **110(1)**. In another example, transformer **120**(R−1) could include a node configured to monitor voltage levels or temperature at transformer **120**(R−1). In yet another example, feeder **130**(S) could include one or more nodes configured to monitor humidity percentages or wind velocities at various locations associated with feeder **130**(S). As a general matter, the nodes within utility network **110** may be smart meters, Internet of Things (IoT) devices configured to stream data, or other computing devices. The nodes within utility network **100** may be configured to record physical quantities associated with power distribution and consumption along utility network **100**, record physical quantities associated with the environment where utility network **100** resides, record quality of service data, or record any other technically feasible type of data.

The nodes residing within utility network **100** are configured to communicate with one another to form an interconnected wireless mesh network. An exemplary wireless mesh network is described in greater detail below in conjunction with FIG. **2**. Back office **150** is coupled to this wireless mesh network and configured to coordinate the overall operation of the network and the corresponding nodes. In doing so, back office **150** configures nodes to record specific data and to establish communication with neighboring nodes. In addition, back office **150** programs the nodes to execute "stream functions" to process incoming time series data, thereby generating data streams. In one embodiment, this configuration is performed in a distributed processing cloud. The incoming time series data could include raw data recorded at the node, or data streams received from neighboring nodes. Back office **150** collects the generated data streams, and, by processing those streams, identifies various events occurring within utility network **100**. Back office **150** may then take specific actions in response to those identified events. Some or all of the processing performed by back office **150** may occur within the distributed processing cloud mentioned above.

FIG. **2** illustrates a mesh network that operates in conjunction with utility network **100** of FIG. **1**, according to one embodiment of the present invention. As shown, a network system **200** includes a wireless mesh network **202**, which may include a source node **210**, intermediate nodes **230** and destination node **212**. Source node **210** is able to communicate with certain intermediate nodes **230** via communication links **232**. Intermediate nodes **230** communicate amongst themselves via communication links **232**. Intermediate nodes **230** communicate with destination node **212** via communication links **232**. Network system **200** may also include an access point **250**, a network **252**, a server **254**, and a router **256**. Network **252** and server **254** may be coupled to a distributed processing cloud **260**, which generally resides outside of network system **200**. As mentioned above in conjunction with FIG. **1**, a given node **230** (or a source node **210** or a destination node **212**) may reside within any of the elements of utility network **100**, including consumers **110**, transformers **120**, and so forth.

A discovery protocol may be implemented to determine node adjacency to one or more adjacent nodes. For example, intermediate node **230-2** may execute the discovery protocol to determine that nodes **210**, **230-4**, and **230-5** are adjacent to node **230-2**. Furthermore, this node adjacency indicates that communication links **232-2**, **232-5**, and **232-6** may be established with nodes **110**, **230-4**, and **230-5**, respectively. Any technically feasible discovery protocol, including one related to IoT principles, may be implemented without departing from the scope and spirit of embodiments of the present invention.

The discovery protocol may also be implemented to determine the hopping sequences of adjacent nodes, i.e., the sequence of channels across which nodes periodically receive payload data. As is known in the art, a "channel" may correspond to a particular range of frequencies. Once adjacency is established between source node **210** and at least one intermediate node **230**, source node **210** may generate payload data for delivery to destination node **212**, assuming a path is available. The payload data may comprise an Internet protocol (IP) packet, an Ethernet frame, or any other technically feasible unit of data. Similarly, any technically feasible addressing and forwarding techniques may be implemented to facilitate delivery of the payload data from source node **210** to destination node **212**. For example, the payload data may include a header field configured to include a destination address, such as an IP address or Ethernet media access control (MAC) address.

Each intermediate node **230** may be configured to forward the payload data based on the destination address. Alternatively, the payload data may include a header field configured to include at least one switch label to define a predetermined path from source node **210** to destination node **212**. A forwarding database may be maintained by each intermediate node **230** that indicates which of communication links **232** should be used and in what priority to transmit the payload data for delivery to destination node **212**. The forwarding database may represent multiple paths to the destination address, and each of the multiple paths may include one or more cost values. Any technically feasible type of cost value may characterize a link or a path within network system **200**. In one embodiment, each node within wireless mesh network **202** implements substantially identical functionality and each node may act as a source node, destination node or intermediate node.

In network system **200**, access point **250** is configured to communicate with at least one node within wireless mesh network **202**, such as intermediate node **230-4**. Communication may include transmission of payload data, timing data, or any other technically relevant data between access point **250** and the at least one node within wireless mesh network **202**. For example, a communication link may be established between access point **250** and intermediate node **230-4** to facilitate transmission of payload data between wireless mesh network **202** and network **252**. Network **252** is coupled to server **254** via a communications link. Access point **250** is coupled to network **252**, which may comprise any wired, optical, wireless, or hybrid network configured to transmit payload data between access point **250** and server **254**.

In one embodiment, server **254** represents a destination for payload data originating within wireless mesh network **202** and a source of payload data destined for one or more nodes within wireless mesh network **202**. Server **254** generally resides within back office **150** of FIG. **1** or is coupled thereto. For example, server **254** could be implemented by a datacenter that includes a number of different computing devices networked together and coupled to back office **150**. In one embodiment, server **254** executes an application for interacting with nodes within wireless mesh network **202**. For example, nodes within wireless mesh network **202** may perform measurements to generate data that reflects operating conditions of utility network **100** of FIG. **1**, including, e.g., power consumption data, among other measurements. Server **254** may execute an application to collect, process, and report those measurements. In one embodiment, server **254** queries nodes **230** within wireless mesh network **202** for certain data. Each queried node replies with the requested data, such as consumption data, system status, health data, and so forth. In an alternative embodiment, each node within wireless mesh network **202** autonomously reports certain data, which is collected by server **254** as the data becomes available via autonomous reporting.

As described in greater detail below in conjunction with FIGS. **4-11**, server **254** is configured to establish and maintain the aforementioned stream network that operates above wireless mesh network **202**. More specifically, server **254** configures the nodes **230** within wireless mesh network **202** to implement "stream functions" in order to process real-time data and generate data streams. A stream function may be any technically feasible algorithm for processing and/or monitoring real-time data. A data stream represents real-time data that is generated by execution of a stream function. The stream network generally includes the various data streams and the paths through mesh network **202** followed by those data streams. The stream network is described in greater detail below in conjunction with FIG. **5**.

In one embodiment, server **150** may interact with distributed processing cloud **260** to perform some or all of the stream network configuration and stream function execution. Distributed processing cloud **260** may be a private or a public distributed processing cloud, or some combination thereof. Distributed processing cloud **260** may define a configurable data processing pipeline that affects a logical data network path above the physical node paths within mesh network **102**.

The techniques described herein are sufficiently flexible to be utilized within any technically feasible network environment including, without limitation, a wide-area network (WAN) or a local-area network (LAN). Moreover, multiple network types may exist within a given network system **200**. For example, communications between two nodes **230** or between a node **230** and the corresponding access point **250** may be via a radio-frequency local-area network (RF LAN), while communications between multiple access points **250** and the network may be via a WAN such as a general packet radio service (GPRS). As mentioned above, each node **230** within wireless mesh network **202** includes a network interface that enables the node to communicate wirelessly with other nodes. An exemplary network interface is described below in conjunction with FIG. **3**.

FIG. **3** illustrates a network interface **300** configured to implement multi-channel operation, according to one embodiment of the invention. Each node **210**, **212**, **230** within wireless mesh network **202** of FIG. **1** includes at least one instance of network interface **300**. Network interface **300** may include, without limitation, a microprocessor unit (MPU) **310**, a digital signal processor (DSP) **314**, digital to analog converters (DACs) **320** and **321**, analog to digital converters (ADCs) **322** and **323**, analog mixers **324**, **325**, **326**, and **327**, a phase shifter **332**, an oscillator **330**, a power amplifier (PA) **342**, a low noise amplifier (LNA) **340**, an antenna switch **344**, and an antenna **346**. A memory **312** may be coupled to MPU **310** for local program and data storage. Similarly, a memory **316** may be coupled to DSP **314** for local program and data storage. Memory **312** and/or memory **316** may be used to store data structures such as, e.g., a forwarding database, and/or routing tables that include primary and secondary path information, path cost values, and so forth.

In one embodiment, MPU **310** implements procedures for processing IP packets transmitted or received as payload data by network interface **300**. The procedures for processing the IP packets may include, without limitation, wireless routing, encryption, authentication, protocol translation, and routing between and among different wireless and wired network ports. In one embodiment, MPU **310** implements the techniques performed by the node, as described in conjunction with FIGS. **2** and **4-11**, when MPU **310** executes firmware and/or software programs stored in memory within network interface **300**.

MPU **314** is coupled to DAC **320** and DAC **321**. Each DAC **320**, **321** is configured to convert a stream of outbound digital values into a corresponding analog signal. The outbound digital values are computed by the signal processing procedures for modulating one or more channels. MPU **314** is also coupled to ADC **322** and ADC **323**. Each of ADC **322** and **323** is configured to sample and quantize an analog signal to generate a stream of inbound digital values. The inbound digital values are processed by the signal processing procedures to demodulate and extract payload data from the inbound digital values. Persons having ordinary skill in the art will recognize that network interface **300** represents just one possible network interface that may be implemented within wireless mesh network **202** shown in FIG. **2**, and that any other technically feasible device for transmitting and receiving data may be incorporated within any of the nodes within wireless mesh network **202**. As a general matter, server **254** of FIG. **2** configures and manages the operation of each node **230** where network interface **300** resides.

FIG. **4**A illustrates server **254** that is coupled to wireless mesh network **202** of FIG. **2**, according to one embodiment of the present invention. As shown, server **254** includes processing unit **400**, input/output (I/O) devices **410**, and memory unit **420**, coupled together. Memory unit **420** includes stream network engine **422**, stream functions **424**, stream software developer kit (SvDK) **426**, and database **428**.

Processing unit **400** may be any technically feasible hardware unit or collection of units configured to process data, including a central processing unit (CPU), a graphics processing unit (GPU), a parallel processing unit (PPU), a field-programmable gate array (FPGA), an application-specific integrated circuit (ASIC), or any combination thereof. Processing unit **400** is configured to perform I/O operations via I/O devices **410**, as well as to read data from and write data to memory unit **420**. In particular, processing unit **400** is configured to execute program code included in stream network engine **400** and SvDK **426**, generate and/or modify stream functions **424**, and read from and/or write to database **428**.

I/O devices **410** may include devices configured to receive input, such as, e.g., a keyboard, a mouse, a digital versatile disc (DVD) tray, and so forth. I/O devices **410** may also include devices configured to generate output, such as, e.g., a display device, a speaker, a printer, and so forth. I/O devices **410** may further include devices configured to both receive input and generate output, such as a touchscreen, a data port, and so forth. I/O devices generally provide connectivity to the Internet, and, specifically, to wireless mesh network **202**.

Memory unit **420** may be any technically feasible unit configured to store data, including a hard disk, random access memory (RAM), etc. The stored data may include structured data sets, program code, software applications, and so forth. Stream network engine **422** is a software application that may be executed by processing unit **400** to establish and maintain the stream network discussed above in conjunction with FIGS. **1-4**, and, further, shown below in FIG. **5**. In doing so, stream network engine **422** configures nodes **230** within mesh network **202** to execute various stream functions **424**. Stream functions **424** may be preconfigured to reside within memory unit **420** of server **254**, e.g., by management associated with back office **150** and mesh network **202**, or may be specified by utility customers of utility grid **100** via SvDK **426**. In one embodiment, the functionality of stream network engine **422** is performed within distributed processing cloud **260** of FIG. **2**. In another embodiment, server **150** executes stream network engine **422** to configure distributed processing cloud **260** to manage nodes **230** and/or execute the stream functions described above.

SvDK **426** is a software application that, when executed by processing unit **400**, provides a development kit to utility customers that allows creation of stream functions **424**. SvDK **426** is a graphical user interface (GUI) that supports drag-and-drop construction of stream functions and/or node monitoring rules, among other possibilities. SvDK **426** is configured to expose an abstract set of libraries to the customer that encapsulates various application programming interface (API) calls. These abstract libraries enable the customer to generate complex stream functions that are implemented by complex underlying code, yet require no actual coding on the part of the customer. An exemplary GUI that may be generated by SvDK **426** is described below in FIG. **4**B.

FIG. **4**B illustrates a GUI **430** that may be used to generate a stream function, according to one embodiment of the present invention. As shown, GUI **430** includes various GUI elements for making different selections and providing various inputs associated with a stream function, including customer selector **432**, input selector **434**, device ID input **436**, name input **438**, attributes selector **440**, interval input **442**, and options buttons **444**. A user of SvDK **426** may interact with GUI **430** in order to define a new stream function for execution by a node **230**.

In practice, the user selects the customer they represent via customer selector **432**, and then identifies, via input selector **434**, the specific inputs from which the new stream function should receive data. Those inputs could be derived from specific devices, including other nodes **230**, or abstract data sources such as Facebook® or Twitter®. The user may also enter a specific device ID via device ID input **436**. The user may then provide a name via name input **438** and select the particular function or functions that should be executed on the source data via attributes selector **440**. Interval selector **442** allows the user to adjust the frequency with which the stream function executes. Options buttons **444** allow various other options to be selected. Once the user has configured GUI **430** to include various selections and inputs, the user may submit the stream function defined by those selections and inputs to server **254**. In response, server **254** then configures distributed processing cloud **260**, nodes **230**, and so forth, to execute that stream function.

Referring back now to FIG. **4**A, SvDK **426** may include server-side code that executes on processing unit **400** as well as client-side code that executes on a remote computing device associated with a utility customer, as well as code that executes on distributed processing cloud **260**. In one embodiment, SvDK **426** may be a web application that provides users with access to a library of function calls for performing data processing on time series data, including raw time series data generated by a node **230** as well as aggregated data stream time series data received from other nodes. The user may specify a stream function by assembling various function calls via the GUI described above in any desired fashion to process the time series data. The library of function calls and other data used by SvDK **426** may be stored in a local database **428**, among other places. Those function calls generally encapsulate specific programmatic operations, including database operations and data processing algorithms, without requiring that the user write actual code. Generally, SvDK **426** allows utility customers to customize a specific portion of the stream network that operates in conjunction with mesh network **202**. The stream network discussed thus far is described in greater detail below in conjunction with FIG. **5-11**.

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FIG. **5** illustrates a stream network **500** configured to operate in conjunction with mesh network **202** of FIG. **2**, according to one embodiment of the present invention. Again, as illustrated in greater detail below, stream network **500** operates above mesh network **202** of FIG. **2** in an overall network architecture. As shown, nodes **230** of mesh network **202** execute stream functions **510** in order to generate data streams **520**.

Specifically, node **230-1** executes stream functions **510-1** to generate data stream **520-1**, node **230-2** executes stream function **510-2** to generate data streams **520-2** and **520-3**, node **230-3** executes stream functions **510-3** to generate data stream **520-4**, node **230-4** executes stream functions **510-4** to generate data streams **520-5** and **520-6**, node **230-5** executes stream functions **510-5** to generate data streams **520-7** and **520-8**, and node **230-6** executes stream functions **510-6** to generate stream function **520-9**. Each data stream **520** includes a time series of data elements, where each data element includes a data value and a corresponding timestamp indicating a time when the data values was recorded or generated.

A given node **230** may execute one or more stream functions **510** to process raw time series data generated by that node **230**. A stream function **510** may be a Boolean operation, such as, e.g., a comparison, or a more complex, higher-level function, such as a correlation operation. The raw time series data processed by stream functions generally includes various types of sensor data, such as voltage data, current measurements, temperature readings, and other types of environmental information. The raw time series data may also include sensor data reflective of the operating conditions of node **230**. Further, the raw time series data may include network status information, traffic measurements, and so forth. In one embodiment, each node **230** is configured to access time series data that is derived from various social media outlets, such as Twitter® or Facebook®, among other possibilities. Node **230** could, for example, retrieve tweets in real-time (or near real-time) via an API provided by Twitter®. Node **230** is configured to process the raw time series data to generate one or more data streams **520**, and to then transmit the generated data stream (s) **520** to neighboring nodes. Data streams generated by processing raw time series data may be referred to herein as "native data streams."

A given node **230** may also execute one or more stream functions **510** to process data streams **520** received from neighboring nodes **230**. A received data stream **520** could be generated by an upstream node **230** based on raw time series data recorded by that node, or generated based on other data streams **520** received by that upstream node. Similar to above, node **230** is configured to process received data streams **520** to generate additional data streams **520**, and to then transmit these data stream(s) **520** to neighboring nodes. Data streams generated by processing other data streams may be referred to herein as "abstract data streams."

Upon generating a data stream **520**, node **230** is configured to transmit the data stream **520** to back office **150** and/or distributed processing cloud **260**, as mentioned. Back office **150** collects data streams **520** from nodes **230** within wireless mesh network **202** and may then perform various additional processing operations with those data streams **520** to identify network events associated with utility network **100** and/or wireless mesh network **202** as well as consumption data. In doing so, server **254** may characterize time series data associated with nodes **230**, including raw time series data and received data streams, and then identify network events associated with abnormal patterns within that time series data. Those network events may include voltage sags/swells, downed power lines, appliance malfunctions, potential fires, and fraud, among others. Server **254** may also process time series data to identify expected or normal patterns, including consumption data, quality of service data, etc. Server **254** may then analyze this data to compute load predictions, demand estimations, and so forth.

For example, a given node **230** could be configured to participate in identifying voltage swells (or sags) by executing a stream function that generates a running average of voltage levels associated with the node **230**. When the voltage level at a given point in time exceeds (or falls below) the running average by a threshold amount, value, node **230** could alert server **254**. Server **254** could then identify that a voltage swell (or sag) is occurring in the region where the node resides. Server **254** could also identify voltage swells or sags by correlating multiple alerts received from multiple nodes **230** residing within the same region. In general, a node **230** may combine data associated with other devices or data streams to draw insights that reflect consumption, service quality and usage, as well as bill forecasts.

In another example, a given node **230** could be configured to execute a stream function that generates a running average of voltage load associated with a transformer to which the node **230** is coupled. When the running average exceeds a threshold level, the node **230** could notify server **254** that a fire may be imminent. The node **230** could also compute the threshold value dynamically by executing a stream function on time series data that reflects ambient temperature associated with the node **230**. The node **230** could then adjust the threshold based on the type of transformer, e.g., by executing a stream function to parse nameplate data associated with that transformer and then generate a nominal load value for that particular type of transformer. The node **230** could also receive the threshold value from server **254**.

In yet another example, a given node **230** could be configured to participate in identifying fraud by executing a stream function to characterize usage patterns associated with a consumer to which the node **230** is coupled and then identify patterns commonly associated with fraud. When a usage pattern commonly associated with fraud is detected, the node **230** could notify server **254**. Such a pattern could be abnormally high consumption compared to neighboring consumers, or divergence between measured load at a transformer coupling a set of meters together and total consumed power at those meters, among other possibilities.

Persons skilled in the art will recognize that stream functions designed for performing computations related to any consumable utility may also be applicable to any other consumable utility. For example, the fraud detection techniques outlined above may be applied to identify loss in the context of water consumption. SvDK **426** of FIGS. **4A-4B** is configured to allow stream functions generated for one utility to be applied to performing analogous computations with another utility.

A given node **230** may identify network events based on parsing data streams collected from a social media outlet (such as the Twitter® API, among others). For example, a data stream gathered from a social media outlet could reflect descriptions of downed power lines, fallen trees, and other events that may impact the functionality of wireless mesh network **202** and utility network **100**. Node **230** could execute a stream function to search that data stream for specific references to such events. Users that contribute to the social media outlet mentioned above would generally create the descriptions included in the data stream in the form of posts, tweets, etc. Node **230** could assign a credibility factor or confidence value to each user in order to validate those descriptions. In this fashion, node **230**, and stream network **500** as a whole, may incorporate qualitative data provided by human beings with some level of confidence.

Generally, stream network **500** may be configured to perform a wide variety of distributed processing operations to identify events occurring within underlying networks, including wireless mesh network **202** and utility network **100**. Stream network **500** may also be configured to perform general processing operations (i.e., beyond event identification). In one embodiment, server **254** within back office **150** and/or distributed processing cloud **260** may implement a map-reduce type functionality by mapping stream functions to nodes, and then reducing data streams generated by execution of the mapped stream functions by collecting and processing those data streams. In this fashion, server **254** is capable of configuring stream network **500** to operate as a generic, distributed computing system. Persons skilled in the art will recognize that server **254** may configure stream network **500** to implement any technically feasible form of distributed processing, beyond map-reduce. Generally, stream network **500** reflects a distributed computing system that combines the processing, extrapolation, interpolation, and analysis of data streams using real-time and historical streams via in-line and parallel batch processing.

In one embodiment, server **254** and/or distributed processing cloud **260** are configured to orchestrate the distribution of processing tasks and/or data storage across the various nodes **230** within stream network **500** in a centralized manner. In doing so, server **254** and/or distributed processing cloud **260** may assign specific processing operations to different nodes, allocate particular amounts of data storage to different nodes, and generally dictate some or all configuration operations to those nodes.

In another embodiment, nodes **230** perform a self-orchestration procedure that occurs in a relatively distributed fashion, i.e. without the involvement of a centralized unit such as server **254** or distributed processing cloud **260**. In doing so, each node **230** may execute a stream function in order to negotiate processing and/or data storage responsibilities with neighboring nodes. Nodes **230** may perform such negotiations in order to optimize energy usage, processing throughput, bandwidth, data rates, etc. For example, nodes **230** could negotiate a distribution of processing tasks that leverages the processing capabilities of solar powered nodes during daylight hours, and then redistributes those operations to nodes powered by utility network **100** during non-daylight hours. In another example, a group of nodes **230** could negotiate coordinated communications using a specific data rate to optimize power consumption. At any given time, server **254** and/or distributed processing cloud **260** may assume direct control over nodes **230**, thereby causing nodes **230** to transition from self-orchestration to centralized orchestration. In a further embodiment, one or more nodes **130** may perform some or all of the functionality associated with server **154**, thereby performing various network management related activities from within wireless mesh network **202**.

Nodes **230** may initiate specific actions based on the execution of one or more stream function **510**. For example, a given node **230** could execute a stream function **510** that compares temperature and humidity values to threshold temperature and humidity values. The node **230** could then determine that both temperature and humidity have exceeded the respective threshold values for a specific amount of time, and then determine that mold growth is likely at the location occupied by the node. The node **230** could then take specific steps to counteract such growth, including activating a ventilation device, or simply notifying back office **150**. Generally, each node **230** is configured to both process and respond to recorded time series data, received data streams, and generated data streams and to generate insights and/or alerts based on such monitoring.

When executing a stream function **510**, a given node **230** may receive control parameters **530** from back office **150** that influence the execution of those stream functions **510**. For example, node **230-1** could receive control parameters **530-1** that reflects an average expected voltage load at node **230-1**. Node **230-1** could record the actual voltage load, compare that recorded value to control parameters **530-1**, and then perform a specific action based on the result, such as, e.g., report to back office **150** a binary value indicating whether the average expected voltage load was exceeded, among other possibilities. In the above example, one of stream functions **510-1** executed by node **230-1** would reflect the comparison operation between actual and expected voltage loads.

In one embodiment, server **254** may configure nodes **230** to operate according to a policy that indicates guidelines for interacting with the nodes of other networks. Each node **230** configured according to the policy may share network resources, route packets according to, and generally interoperate with those other nodes based on the policy. For example, node **230** could be configured according to a policy that indicates that 40% of traffic received from a network adjacent to the wireless mesh network **202** should be accepted and routed across wireless mesh network **202** on behalf of the adjacent network. In another example, node **230** could be configured according to another policy that indicates that traffic from a first adjacent network should be routed according to a first set of guidelines, while traffic associated with a second adjacent network should be routed according to second set of guidelines. In yet another example, node **230** could be configured according to a policy that specifies how traffic received from one adjacent network should be routed across wireless mesh network **202** in order to reach another adjacent network. The technique described herein allows new nodes **230** to be added to wireless mesh network and then configured according to the same policy or policies already associated with other pre-existing nodes **230** in the wireless mesh network **202**. In addition, this technique allows wireless mesh network **202** to operate in a relatively consistent manner across nodes **230** without requiring continuous querying of server **254** with regard to routing decisions. Instead, nodes **230** need only operate according to the configured policy.

As a general matter, different nodes **230** within stream network **500** may receive different control parameters **530**.

Each such node **230** may execute stream functions **510**, based on received control parameters **530**, to process raw time series data and/or received data streams **520**. When processing raw time series data, a node **230** may perform error detection and/or correction to modify that time series data, and may also split a given time series into two or more separate time series, as described in greater detail below in conjunction with FIG. **6**.

FIG. **6** illustrates an exemplary scenario where a node of FIG. **5** generates a set of data streams based on recorded time series data, according to one embodiment of the present invention. As shown, node **230** records time series **600**, **610**, and **620** and receives control parameter **630**. Node **230** executes stream functions **602**, **612**, and **622** with the received time series and, potentially, control parameters **630**, in order to generate data streams **604**, **606**, **614**, and **624**.

Time series **600**, **610**, and **620** generally include a series of ordered pairs, where each ordered pair includes a datum and a time stamp. The datum in a given ordered pair could be, e.g., a specific sensor reading, or, alternatively, a collection of sensor readings. The time stamp reflects a specific time when the datum was recorded or computed. Occasionally, portions of a given time series may be corrupted or missing. For example, time series **620** includes a corrupted ordered pair, as is shown. Node **230** is configured to detect missing and/or corrupted data and to take specific action to mitigate such issues. For example, node **230** could execute stream function **612** to substitute a valid ordered pair into time series **610** in place of the missing ordered pair. The substitution operation could be, e.g., a forward-fill operation, among others. Alternatively, node **230** could incorporate a placeholder ordered pair indicating that no data is available for the corresponding time. In other situations, node **230** could execute a stream function to perform error correction, thereby repairing ordered pairs subject to recoverable forms of data corruption. With this approach, network traffic can be reduced because corrupted data need not be transmitted to server **254** for repair. Instead, the data is repaired prior to transmission. In some cases, only a much smaller subset of the computed outputs from data streams can be transmitted to further reduce network bandwidth needs and data latency.

Node **230** is also configured to separate individual time series into multiple, distinct time series. For example, node **230** could execute stream function **602** to separate time series **600** into data streams **604** and **606**. As is shown, each ordered pair of time series **600** includes a voltage value and current value recorded at a particular time. Node **230** could execute stream function **602** to generate data stream **604** that reflects only the voltage values from time series **600** as a function of time, as well as data stream **606** that reflects only the current values from time series **600** as a function of time.

In one embodiment, data streams associated with related portions of stream network **500**, wireless mesh network **202**, and/or utility network **100** may be grouped together in a logical fashion to create "stream structures." For example, a stream structure could include a data stream associated with a transformer that reflects load associated with the transformer. The stream structure could also include one or more data streams associated with smart meters coupled downstream of that transformer and configured to measure downstream consumption. A given node **230** may be configured to group data streams into a stream structure, or server **254** may be responsible for performing that grouping. Grouping data streams in this fashion allows utility customers to generate stream functions that perform computations on an entire stream structure, making certain types of computations simpler to manage.

Persons skilled in the art will understand that node **230** may perform any technically feasible form of real-time data processing to convert a received time series into a data stream. In addition, node **230** may process received data to identify events associated with that data, and then generate a data stream that reflects those events. In this manner, node **230** may be configured to generate a real-time status report. Such a report may reflect the status of node **230** or the network environment associated with node **230**. The overall network architecture where node **230** resides, including utility network **100**, wireless mesh network **202**, and stream network **500**, is described in greater detail below in conjunction with FIG. **7**.

FIG. **7** illustrates a network architecture **700** that includes utility network **100** of FIG. **1**, wireless mesh network **202** of FIG. **2**, and stream network **500** of FIG. **5**, according to one embodiment of the present invention. As shown, stream network **500** resides above wireless mesh network **202**, which, in turn, resides above utility network **100**. Utility network **100** includes the various network elements shown in FIG. **1**, and wireless mesh network includes the various nodes **230** discussed above in conjunction with FIGS. **2-3** and **5**. As also shown, stream network **500** is subdivided into a private cloud **710** and a public cloud **720**. Each of private cloud **710** and public could **720** includes a different set of customer sub-networks **500-1** through **500-4**. Customer sub-networks **500-1** through **500-4** generally reflect different portions of stream network **500** that may be configured independently.

In one embodiment, customer sub-networks **500-1** and **500-2** include shared sets of nodes **230**, while customer sub-networks **500-3** and **500-4** include separate, dedicated sets of nodes **230**. As a general matter, a given customer subscribes to specific data streams generated by the customer sub-network with which that customer is associated. Each customer sub-network **500-1** through **500-4** may be separately configurable and can be maintained, using the techniques previously described for managing stream network **500**, by back office **150**.

Referring generally to FIGS. **1-7**, the network architecture described thus far allows complex, distribute processing to occur at edge locations associated with nodes within that network architecture. Accordingly, data that would otherwise be transmitted to back office **150** for processing can, instead, be processed at or near the location where that data is actually collected. Therefore, data processing can occur in real-time, i.e. while the data is "in-flight," and without substantially increasing network traffic.

In one embodiment, stream network **500** may be integrated into a datacenter and each node **230** of that network may be configured to monitor various qualities of a particular server within that datacenter. A given node **230** may measure temperature, utilization, task load, input/output (I/O) operations, location, and so forth, for a particular server in order to determine the operational status of that server. Stream network **500** as a whole may then aggregate status information across all servers in the datacenter and identify (i) particular servers that are overloaded and should not be assigned new tasks, and (ii) other servers that are underutilized and should be assigned new tasks. Among other things, this approach allows stream network **500** to optimize the speed of I/O operations within the datacenter because tasks involving heavy I/O operations can be assigned to low-temperature servers rather than high-temperature servers, thereby increasing the speed with which those I/O operations may be performed.

The techniques described thus far are also described, in stepwise fashion, below in conjunction with FIGS. **8**-**11**.

FIG. **8** is a flow diagram of method steps for generating a data stream based on recorded time series data, according to one embodiment of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1**-**7**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.

As shown, a method **800** begins at step **802**, where a node **230** within wireless mesh network **202** of FIG. **2**, configured to implement a portion of stream network **500** of FIG. **5**, receives a stream of control parameters from server **254** within back office **150**. The control parameters generally include values to be input to stream functions executed by the node **230**. Those values could include, for example, a time-varying average of a quantity measured by the node **230**, a threshold value for such a quantity, above which safety issues may arise, or other times of values that influence the execution of a stream function.

At step **804**, the node **230** records raw time series data via a sensor array coupled thereto. The node **230** may record a wide variety of different types of data, including environmental data associated with a location where node **230** resides, status information associated with node **230** or the various networks with which node **230** is associated, and other data that varies over time.

At step **806**, the node **230** executes a first stream function to detect and/or correct missing or corrupted data in the raw time series data, thereby generating pre-processed data. Node **230** could, for example, determine that the raw time series data has a particular frequency, and therefore should include data for specific intervals of time, and then identify that data is missing for one such interval. Node **230** could also, in another example, perform an error-checking procedure to determine that data in the time series is corrupted. In various embodiments, step **806** may be omitted.

At step **808**, the node **230** executes a second stream function to generate one or more data streams based on the pre-processed data. In one embodiment, the node **230** separates the pre-processed data into two or more other time series, thereby generating two or more new data streams. Data streams created in this fashion may be referred to as "native streams" as those streams essentially include raw time series data. The node **230** may also execute the second stream function based on other time series data recorded by the node **230**. For example, the node **230** could execute a stream function that compares the pre-processed time series data to another set of time series data, and then generate a new data stream to reflect the result of that comparison.

At step **810**, the node **230** transmits the data streams generated at step **808** to one or more neighboring nodes. Each node **230** that receives the data streams transmitted at step **810** may then, in turn, implement a technique for processing received data streams to generate new data streams, as described below in conjunction with FIG. **9**. In one embodiment, the steps of method **800** are implemented as a "data pipeline" which is defined by SvDK **426** and executed dynamically by the underlying compute architecture of stream network **500**.

FIG. **9** is a flow diagram of method steps for generating one or more data streams based on one or more received data streams, according to one embodiment of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1**-**7**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.

As shown, at step **902**, a node **230** receives a stream of control parameters from server **254** within back office **150**, similar to step **802** of the method **800**. At step **904**, the node **230** receives a plurality of data streams from neighboring, upstream nodes. The upstream nodes may have generated those data streams based on recorded time series data, or, alternatively, may have generated those data streams based on other received data streams. At step **906**, the node **230** executes one or more stream functions with the plurality of data streams to generate one or more additional data streams. At step **908**, the node **230** transmits the additional data streams to neighboring, downstream nodes.

Referring generally to FIGS. **8**-**9**, persons skilled in the art will understand that an individual node **230** may implement the methods **800** and **900** simultaneously. In addition, an individual node **230** may implement certain steps of the method **800** in conjunction with certain steps of the method **900**. For example, a node **230** may execute a given stream function with raw time series data recorded by the node **230** and, additionally, with one or more data streams received by that node.

Server **254** within back office **150**, or a collection of servers associated with a datacenter, generally configures nodes **230** within wireless mesh network **202** to implement stream network **500**, as previously described herein. Server **254** may then identify various events that may occur within utility network **100** or wireless mesh network **202** by implementing a technique described in greater detail below in conjunction with FIG. **10**.

FIG. **10** is a flow diagram of method steps for evaluating conditions associated with network architecture of FIG. **7**, according to one embodiment of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1**-**7**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.

As shown, a method **1000** begins at step **1002**, where server **254** within back office **150** receives data streams from nodes **230** within wireless mesh network **202** configured to implement stream network **500**. Each such node could be configured, for example, to implement either or both of the methods **800** and **900** discussed above in conjunction with FIGS. **8**-**9**, respectively.

At step **1004**, server **254** identifies stream-level events associated with the received data streams. As referred to herein, a "stream-level event" generally includes any event that is identifiable based on a single data stream. Server **254** could identify, for example, patterns within a particular data stream, or determine that a value associated with a particular data stream exceeds a preset value maintained by server **254**, among other possibilities.

At step **1006**, server **254** identifies network-level events by correlating data streams or stream-level events with one another. For example, server **254** could identify a power outage or onset of a power outage in a given region by determining that a collection of data streams associated with that region have deviated from respective nominal values by a threshold amount in a correlated fashion consistent with past outage patterns. Server **254** may implement a wide variety of different techniques for correlating data, thereby identifying a multitude of different events within utility network **100** and/or wireless mesh network **202**. When processing data streams in the fashion described herein, server **254** may generate a time series of results, where each element of the results time series is generated by processing one or more elements of received data streams and corresponding timestamps.

At step **1008**, server **254** initiates one or more actions in response to the identified events. Server **254** may issue commands to individual nodes **230** or groups of nodes **230**, including commands for modifying the operating state of those nodes. Server **254** may also power down specific nodes, activate other nodes, or adjust pathways between nodes. Any type of network-oriented action falls within the scope of the present invention. Server **254** may also interact with customers of utility network (or others associated with utility network) **100** in order to customize portions of stream network **500** to implement specific stream functions, as described in greater detail below in conjunction with FIG. **11**.

FIG. **11** is a flow diagram of method steps for configuring a node within the stream network of FIG. **5** to generate a data stream, according to one embodiment of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1-7**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.

As shown, a method **1100** begins at step **1102**, where SvDK **426** within server **254** receives a stream function specification. SvDK **426** is a software application configured to generate a user interface through which a user may define a stream function. SvDK **426** could be, for example, a programming environment associated with one or more specific programming languages, or, alternatively, a graphical user interface (GUI) that supports drag-and-drop construction of stream functions, among other possibilities. SvDK **426** may include server-side code that executes on processing unit **400** as well as client-side code that executes on a remote computing device.

At step **1104**, SvDK **426** designates one or more specific nodes **230** to execute the stream function specified at step **1102**. SvDK **426** may also receive a specific designation from the user of SvDK **426**. At step **1106**, SvDK **426** pushes the stream function to the nodes **230** designated at step **1104**, thereby configuring those nodes to execute the stream function. At step **1108**, SvDK **426** causes the designated nodes **230** to generate new data streams by executing the stream functions. A designated node **230** could execute a new stream function with raw time series data recorded by the node and/or with data streams received by the node. At step **1110**, SvDK **426** initializes a portal that provides access to the new data streams. The portal could be, for example, a web address that is periodically updated to reflect one or more values associated with the new data streams. In one embodiment, SvDK **426** may also allow the user to specify actions that should be initiated under certain circumstances relative to the newly-configured data streams, including issuing alerts or performing network-level actions.

By implementing the method **1100**, SvDK **426** provides a customer of the utility network with the ability to configure a portion of stream network **500** to capture and/or generate specific types of real-time data. Accordingly, a given customer may leverage the computing power of stream network **500** to more effectively manage the operation of utility network **100**.

In sum, nodes within a wireless mesh network are configured to monitor time series data associated with a utility network (or any other device network), including voltage fluctuations, current levels, temperature data, humidity measurements, and other observable physical quantities. The nodes execute stream functions to process the recorded time series data and generate data streams. The node is configured to transmit generated data streams to neighboring nodes. A neighboring node may execute other stream functions to process the received data stream(s), thereby generating additional data streams. A server coupled to the wireless mesh network collects and processes the data streams to identify events occurring within the network. The techniques described herein allow the delivery of "data-as-a-service" (DaaS) that represents an interface between the traditional software-as-a-service (SaaS) and platform-as-a-service (PaaS) approaches.

One advantage of the techniques set forth herein is that the stream network allows network processing to occur at edges of the network, i.e., locations within the stream network where data is actually collected. Thus, complex processing involving the network as a whole can be broken down into granular, atomic processing steps that are performed, in a distributed fashion, across the stream network, thereby more effectively leveraging the processing power of the network. In addition, since the data is recorded and then shortly thereafter processed, that data can be processed in a real-time fashion that is not feasible with prior art approaches.

The descriptions of the various embodiments have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments.

Aspects of the present embodiments may be embodied as a system, method or computer program product. Accordingly, aspects of the present disclosure may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a "circuit," "module" or "system." Furthermore, aspects of the present disclosure may take the form of a computer program product embodied in one or more computer readable medium(s) having computer readable program code embodied thereon.

Any combination of one or more computer readable medium(s) may be utilized. The computer readable medium may be a computer readable signal medium or a computer readable storage medium. A computer readable storage medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific examples (a non-exhaustive list) of the computer readable storage medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

Aspects of the present disclosure are described above with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems) and computer program products according to embodiments of the disclosure. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, enable the implementation of the functions/acts specified in the flowchart and/or block diagram block or blocks. Such processors may be, without limitation, general purpose processors, special-purpose processors, application-specific processors, or field-programmable processors.

Embodiments of the disclosure may be provided to end users through a cloud computing infrastructure. Cloud computing generally refers to the provision of scalable computing resources as a service over a network. More formally, cloud computing may be defined as a computing capability that provides an abstraction between the computing resource and its underlying technical architecture (e.g., servers, storage, networks), enabling convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction. Thus, cloud computing allows a user to access virtual computing resources (e.g., storage, data, applications, and even complete virtualized computing systems) in "the cloud," without regard for the underlying physical systems (or locations of those systems) used to provide the computing resources.

Typically, cloud computing resources are provided to a user on a pay-per-use basis, where users are charged only for the computing resources actually used (e.g. an amount of storage space consumed by a user or a number of virtualized systems instantiated by the user). A user can access any of the resources that reside in the cloud at any time, and from anywhere across the Internet. In context of the present disclosure, a user may access applications (e.g., video processing and/or speech analysis applications) or related data available in the cloud.

The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods and computer program products according to various embodiments of the present disclosure. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function (s). It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

While the preceding is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

The invention claimed is:

1. One or more non-transitory computer-readable media storing program instructions that, when executed by one or more processors of a network, cause the one or more processors to generate a time series of data values, the network comprising a plurality of nodes and a back office server, by performing the steps of:

obtaining, from a first sensor array at the first node, a first time series of data values having a first type;

obtaining, at the first node, a second time series of data values having a second type;

executing, at the first node, a first stream function on at least a portion of the first time series and at least a portion of the second time series to generate a third time series of data values having a third type;

transmitting the third time series of data values to a second node in the network;

executing, at the first node, a negotiating function for distributing processing responsibilities to the first node during daylight hours and distributing processing responsibilities to the second node during non-daylight hours, wherein the first node comprises a solar powered node, and the second node comprises a utility powered node; and

based on the third time series of data values, issuing, by the second node, one or more commands to a third node that cause the third node to perform at least one of activating the third node or powering down the third node.

2. The one or more non-transitory computer-readable media of claim **1**, the steps further comprising:

causing the first sensor array that is configured to record data values of the first type to generate the first time series of data values; and

causing a second sensor array that is configured to record data values of the second type to generate the second time series of data values.

3. The one or more non-transitory computer-readable media of claim **1**,

wherein the second time series of data values is received from another node in the network, and

wherein the another node includes a second sensor array that is configured to record data values of the second type.

4. The one or more non-transitory computer-readable media of claim **1**, the steps further comprising:

causing the first sensor array that is configured to record data values of the first type to generate the first time series of data values,

wherein the second time series of data values is received from another node in the network, and

wherein the another node includes a second sensor array that is configured to record data values of the second type.

5. The one or more non-transitory computer-readable media of claim **1**, the steps further comprising:

obtaining a fourth time series of data values having a fourth type; and

executing a second stream function to separate the fourth time series of data values into a fifth time series of data values having a fifth type and a sixth time series of data values having a sixth type.

6. The one or more non-transitory computer-readable media of claim **1**, the steps further comprising performing an error-correction procedure against at least one of the first time series of data values or the second time series of data values to correct missing or corrupted data.

7. The one or more non-transitory computer-readable media of claim 1, the steps further comprising:

grouping the first time series of data values, the second time series of data values, and the third time series of data values into a first stream structure; and

transmitting the first stream structure to at least one node in the network, wherein the first stream structure includes one or more data values associated with a component included within an electricity distribution infrastructure.

8. The one or more non-transitory computer-readable media of claim 1, wherein each data value in the first time series of data values reflects a computed attribute associated with the second time series of data values, and wherein each data value in the third time series of data values reflects a result associated with comparing a data value from the second time series of data values to a data value from the first time series of data values.

9. The one or more non-transitory computer-readable media of claim 8, wherein a first computed attribute comprises an average value associated with a plurality of data values in the second time series of data values, and wherein the result associated with comparing indicates whether a data value from the second time series of data values exceeds a data value from the first time series of data values.

10. The one or more non-transitory computer-readable media of claim 1, wherein executing the first stream function comprises comparing at least the portion of the first time series to at least the portion of the second time series to generate the third time series of data values.

11. The one or more non-transitory computer-readable media of claim 10, wherein the third time series of data values comprises results of the comparison.

12. The one or more non-transitory computer-readable media of claim 1, the steps further comprising identifying, at the second node, a first event associated with the network based on the third time series of data values, and determining the one or more actions based on the first event.

13. The one or more non-transitory computer-readable media of claim 1, wherein the one or more actions modify an operating state of the third node in the network.

14. The one or more non-transitory computer-readable media of claim 1, the steps further comprising:

executing, at the first node, a negotiating function for negotiating a particular data rate with the second node for coordinated communications with the second node.

15. The one or more non-transitory computer-readable media of claim 1, the steps further comprising:

receiving, at the first node and from the back office server, at least one control parameter, wherein executing the first stream function comprises executing the first stream function based on the at least one control parameter.

16. A system configured to generate a time series of data values, comprising:

a first node that resides within a network comprising a plurality of nodes and a back office server, the first node including:

a memory configured to store program code, and

a processor that is coupled to the memory and, when executing the program code, is configured to:

obtain, from a first sensor array, a first time series of data values having a first type,

obtain a second time series of data values having a second type,

execute a first stream function on at least a portion of the first time series and at least a portion of the second time series to generate a third time series of data values having a third type,

transmit the third time series of data values to a second node in the network, and

execute a negotiating function for distributing processing responsibilities to the first node during daylight hours and distributing processing responsibilities to the second node during non-daylight hours, wherein the first node comprises a solar powered node, and the second node comprises a utility powered node; and

the second node configured to:

based on the third time series of data values, issue one or more commands to a third node that cause the third node to perform at least one of activating the third node or powering down the third node.

17. The system of claim 16, wherein the first node further includes:

the first sensor array that is coupled to an underlying network and is configured to record, from the underlying network, data values of the first type to generate the first time series of data values, and

a second sensor array that is coupled to the underlying network and configured to record, from the underlying network, data values of the second type to generate the second time series of data values.

18. The system of claim 16, further comprising:

a first upstream node, including the first sensor array that is coupled to an underlying network and configured to record, from the underlying network, data values of the first type for transmission to the first node; and

a second upstream node, including a second sensor array that is coupled to the underlying network and configured to record, from the underlying network, data values of the second type for transmission to the first node,

wherein the first node, the first upstream node, and the second upstream node are configured to exchange a plurality of time series of data values in order to form an overarching network.

19. The system of claim 16, wherein the first node further includes:

the first sensor array that is coupled to an underlying network and configured to record, from the underlying network, data values of the first type to generate the first time series of data values; and

the processor is further configured to receive the second time series of data values from a second upstream node in the network, wherein the second upstream node includes a second sensor array that is coupled to the underlying network and configured to record, from the underlying network, data values of the second type,

wherein the first node and the second upstream node are configured to exchange a plurality of time series of data values in order to form an overarching network.

20. The system of claim 16, wherein the processor is further configured to obtain a fourth time series of data values having a fourth type; and

execute a second stream function to compress the fourth time series of data values into a fifth time series of data values having the fourth type.

21. The system of claim 16, wherein a data value having the first type comprises a first measurable or computable attribute of a portion of an electricity distribution infrastructure underlying the network, wherein a data value having the second type comprises a second measurable or computable

attribute of the portion of the electricity distribution infrastructure underlying the network.

22. The system of claim **16**, wherein the first time series of data values and the second time series of data values are derived from an underlying network, and the third time series of data values comprises a portion of an overarching network.

23. A computer-implemented method for generating a time series of data values, the method comprising:

obtaining, from a first sensor array at a first node included in a network comprising a plurality of nodes and a back office server, a first time series of data values having a first type;

obtaining, at the first node, a second time series of data values having a second type;

executing, at the first node, a first stream function on at least a portion of the first time series and at least a portion of the second time series to generate a third time series of data values having a third type;

transmitting the third time series of data values to a second node in the network;

executing, at the first node, a negotiating function for distributing processing responsibilities to the first node during daylight hours and distributing processing responsibilities to the second node during non-daylight hours, wherein the first node comprises a solar powered node, and the second node comprises a utility powered node; and

based on the third time series of data values, issuing, by the second node, one or more commands to a third node that cause the third node to perform at least one of activating the third node or powering down the third node.

24. The computer-implemented method of claim **23**, further comprising:

causing the first sensor array that is configured to record data values of the first type to generate the first time series of data values; and

causing a second sensor array that is configured to record data values of the second type to generate the second time series of data values, or

receiving the second time series of data values from another node in the network that is configured to record data values of the second type from the underlying network.

25. The computer-implemented method of claim **23**, further comprising:

generating a user interface that reflects a plurality of time series of data values and a plurality of stream functions;

receiving a first selection of the first time series of data values from within the plurality of time series of data values;

receiving a second selection of the second time series of data values from within the plurality of time series of data values;

receiving a third selection of the first stream function; and

configuring another node within the network based on the first selection, the second selection, and the third selection.

26. The computer-implemented method of claim **25**, wherein the first node obtains the first time series of data values and the second time series of data values based on sensor readings associated with an underlying network, and wherein the first node transmits the third time series of data values to form a portion of an overarching network.

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